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Final Technical Report
April 1975

DESIGN STUDY FOR WASS LANDING MONITOR SYSTEM

Teledyne Micronetics

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Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, New York 13441

PREFACE

This Final Report was prepared by Teledyne Micronetics, 7155 Mission Gorge Road, San Diego, California 92120 under Contract No. F30602-74-C-0254 with Rome Air Development Center, Griffiss Air Force Base, New York 13441. The RADC Project Engineer was Mr. Cy Edmunds (OCD).

The program was directed by Dr. Steven Weisbrod, the company's Chief Scientist. Other principal contributors to the efforts were Mr. A. J. Hannum, Chief Engineer, Mr. L. A. Morgan, Senior Scientist and Mr. P. A. Hicks, Head Electronic Design.

Special thanks are due to the Air Force Avionics Laboratory at Wright-Patterson Air Force Base and in particular to Mr. Robert L. Davis of that laboratory for the assistance in making available some of the experimental equipment utilized in this effort. Also special acknowledgement is due to Data-Ware Corporation of San Diego, California for their expertise recommendations regarding real time data reduction techniques which are described in Section 10.2 of this report.

This technical report has been reviewed and approved for publication.

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The report is a system design study of a Landing Monitor utilizing L-band transponder transmissions from the approaching aircraft. The system is specifically designed to provide accurate and reliable vertical angle information under the conditions of severe multipath from the antenna foreground.

The principle of operation is the Wavefront Analysis through Spatial Sampling or the WASS. The WASS technique was experimentally demonstrated in a previous

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effort and the extrapolation of those results to a typical airport geometry indicates that the WASS Landing Monitor should be capable of tracking the downcoming aircraft to within 30 feet above the runway with an accuracy of about $\pm$ 2 feet.

The system design study is aimed toward the development of an experimental unit which could be tested and evaluated at an Air Force installation using Air Force test planes. For this reason the emphasis was placed on parts of the system which deal with the vertical tracking. The azimuthal tracking which can be implemented through standard monopulse and the integration of the display with existing GCA equipment, both of which will be incorporated into operational units, have not been considered in detail at this time.

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EVALUATION

Wavefront Analysis through Spatial Sampling is a multipath elimination technique based upon the measurement of amplitude and relative phase of an incident signal over a given aperture, subjecting it to computer analysis and separating the direct and indirect components of the complex wave. The proposed system will include a ground station operating in conjunction with the airborne ATCRBS transponder to provide range, azimuth angle and elevation angle data. It should be pointed out that it would also be possible to utilize aircraft interrogations from DME or TACAN equipment. In this case, range would be determined by triangulation as described in the report.

Applications for the WASS technique include but are not limited to the following: (1) an independent monitor system for ILS and MLS, (2) operation as a manual low approach system in a GCA mode, (3) with the addition of a data link it can operate in a landing system mode, and (4) as a backup for GCA systems to be used during periods of extremely heavy precipitation.

Cyril M. Edmunds

CYRIL M. EDMUNDS
Contract Engineer

SECTION I

INTRODUCTION

1.1 GENERAL INFORMATION

This is the Final Report prepared for the Rome Air Development Center under Contract No. F30602-74-C-0254. The effort is a design study for an aircraft landing monitor system utilizing standard aircraft L-band transponder emissions in combination with Wavefront Analysis through Spatial Sampling (WASS).

The current Precision Approach Radars (PAR's) are not capable of Category III landings for reasons which are common to all tracking radars operating at low elevation angles, namely the ground-reflected multipath. Some relief from multipath can be obtained by the use of narrow antenna beams and short pulses but even these begin to fail when the elevation angle drops much below two degrees. In the airport environment, construction of large-aperture antennas near the runway is inconsistent with air traffic safety and this precludes the use of extremely narrow beamwidths at frequencies which are low enough not to be adversely affected by inclement weather. Similarly the use of narrow pulses is also limited. To achieve time separation between direct and ground-reflected signals when the aircraft is 5,000 feet away and 100 feet above the runway, requires utilization of subnanosecond pulses, which generates many practical problems.

To obtain reasonable beamwidths with reasonably sized antennas PAR operates at X-band. While this permits generation of a one-degree beamwidth with a five-foot aperture, X-band radar is adversely affected by bad weather. Utilization of circular polarization helps to alleviate the clutter problem but it does not help the signal attenuation.

Ideally one would like to use lower frequency signals, but a longer wavelength implies antenna beamwidths of several degrees which in turn means more interference from ground reflection. For instance, if one should select L-band and would like to track the aircraft down to about a quarter of a degree in elevation, one would need an antenna aperture of about 200 feet which is not practical for landing monitoring application.

The WASS technique is designed to counteract and even to utilize the normally debilitating effects of multipath encountered by tracking radars at low angles of elevation. Unlike the conventional techniques which try to minimize the foreground

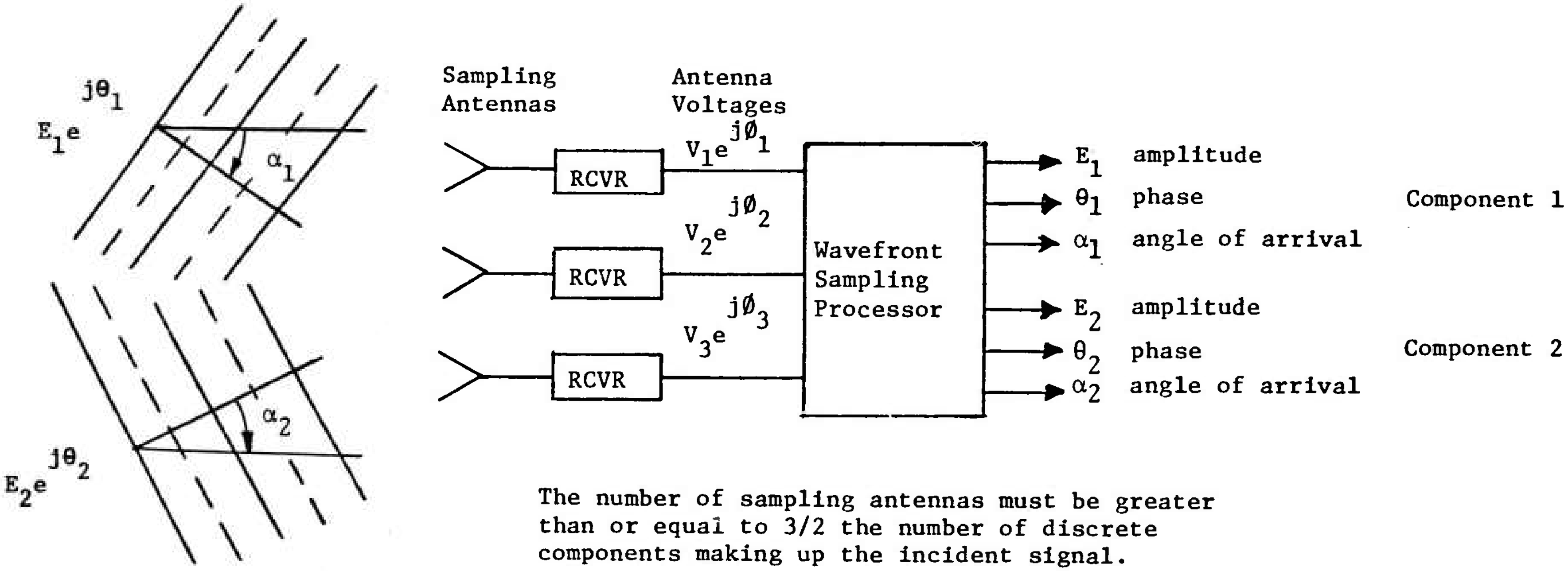
multipath by beam shaping or ignore its existence until it kills the system performance, the WASS is specifically designed to recognize the presence of multipath and to separate and measure the angles of arrival of the direct and the reflected components even though the angular separation between the two may be a fraction of the antenna array equivalent half power beamwidth. Furthermore, under certain conditions where the ground reflection is very well defined, it will be possible to use the ground reflected component to form an equivalent wide base free space vertical interferometer whose base line is twice the height of the WASS antenna and even further improve the potential accuracy of the system.

The very impressive resolving power of the WASS technique was experimentally demonstrated under a previous RADC sponsored effort under Contract F30602-72-C-0344. If these results are extrapolated to L-band and if it is assumed that the tracking signal is the standard L-band transponder, it should be possible, using a 30 foot structure 500 feet to one side of the runway center, to track an incoming aircraft and its ground reflected image down to within 30 feet above the ground with an accuracy of about 2 feet provided that the range to the aircraft is known to within 100 feet using calibrated beacon delay or an independent range measurement with a radar or a horizontal wide base interferometer.

The principles of the Wavefront Sampling are reviewed in Section 3. For the purpose of introductory remarks it will suffice to state that the essential feature of the WASS is to vertically sample the phase and the amplitude of the incident signal at several points in space and then by means of appropriate algebraic algorithms to resolve the incident field into the direct and the ground-reflected components. This is illustrated in Figure 1-1. A minimum of three sampling antennas are required to resolve the direct and the reflected components. For reasons which will be explained in Section 7, five vertical sampling antennas with nonuniform spacing are recommended for this application.

In order to make this report as self contained as possible important theoretical and experimental results of previous efforts are summarized in Section 3. In addition, a new and a more efficient solution of the WASS equations which was developed in the course of this effort is described in Section 3.4.

Section 4 gives a conceptual overview of the WASS landing monitor as it is currently envisioned. This section sets the stage for the detailed discussion of the various subsystems which are discussed in Sections 5 through 11.



The number of sampling antennas must be greater than or equal to 3/2 the number of discrete components making up the incident signal.

FIGURE 1-1

PRINCIPLE OF WAVEFRONT SAMPLING ANALYSIS

Section 12 describes the definitive tests and evaluation procedure which must be carried out to realistically assess and experimentally verify the high potential capability of the WASS system under simulated operational environment using real aircraft and real runways.

Section 13 contains conclusions and recommendations.

1.2 STATEMENT OF THE PROBLEM

The current Precision Approach Radars are not capable of Category III landings because of multipath contamination. To obtain narrower beams it would be necessary either to build larger antennas or go to higher frequencies. Larger antenna structures are incompatible with runway safety requirements and higher frequencies would be very adversely affected by bad weather which is precisely when additional landing monitoring capabilities are most needed. Even the current X-band PAR are severely hampered by bad weather. This is probably a contributing reason why PAR will be eventually phased out in favor of air derived systems such as ILS and MLS.

There is, however, a continuing need for an inexpensive and independent land based monitoring system which could, in an emergency, provide adequate guidance to the incoming aircraft to bring it down safely under adverse weather conditions.

The WASS Landing Monitor (WASS-LM) offers this capability. As it is presently conceived WASS-LM will utilize the existing L-band transponders on the aircraft and therefore would not require any additonal equipment aboard the aircraft. Furthermore, since the L-band is relatively unaffected by the inclement weather, the system should provide a high degree of reliability in heavy rain, snow, and fog.

The design study described in this report demonstrates that the WASS system should be rather inexpensive which should make it attractive for extensive deployment at Air Force installations.

1.3 SCOPE OF THE EFFORT

Scope of the effort described in this report is two-fold. First, it was recognized that there is always a large gap between a laboratory demonstrated capability which WASS is and a real life operational capability which has yet to be demonstrated. Consequently, it was decided that the immediate goal of the effort should be directed toward a definitive field test and evaluation even though such evaluation would be restricted only to the

vertical angle resolving and tracking capability to evaluate the essential features of the WASS technique. At the same time it was felt that the design study should take into consideration the total operational system which would be capable of ranging, azimuth tracking, and integration with the existing ground control capabilities. This dual approach was utilized whenever possible throughout the effort in order to insure that most of the results of this study would be directly applicable to the full system at a later date.

SECTION II
SUMMARY

The report describes in detail a Landing Monitor System utilizing Wavefront Sampling (WASS) Technique on signals from the L-Band transponder aboard the aircraft. Previously carried out tests indicate that the WASS Landing Monitor should be capable to provide reliable aircraft tracking information down to 30 feet above the runway with a typical accuracy of about ±2 feet. Since the use is made of existing L-Band transponders no additional equipment costs to the aircraft would be incurred. The cost of the WASS Landing Monitor system is estimated at less than $200,000.

The report divides the WASS Landing Monitor with several major subsystems and each subsystem is considered in detail. The major subsystems are the antenna, the front end, the receiver main frame, the calibration system, the interrogation and ranging, the data processor and the data display.

Since the thrust of the study is aimed at the development of the essential features of the WASS system to demonstrate and evaluate the capability of the system under controlled operational environment, certain aspects of the system such as azimuthal tracking and data display were de-emphasized since these capabilities are routinely available and could be added at a later time. Instead the emphasis was placed on the key problems of accurate vertical tracking in the presence of strong foreground multipath.

The study has clearly demonstrated that an inexpensive operational prototype of the WASS landing system could be developed within two years and could provide the Air Force with a reliable, accurate all-weather landing monitoring system which would significantly increase the safety or aircraft landing under adverse weather conditions.

SECTION III

REVIEW OF THE WASS CONCEPT

3.1 GENERAL DISCUSSION

In order to make this report as self-inclusive as possible the underlying features of the WASS concept, the basic equations and experimental results will be summarized. Many details will be omitted and for more comprehensive discussions the reader will be asked to consult previously published RADC Technical Reports; RADC-TR-71-262 and RADC-TR-73-302.

Wavefront Sampling is a technique which records the phase and amplitude of the incident wavefront at several points within the antenna aperture and processes this spatial information to resolve the incident field into discrete plane wave components. Since each plane wave component is represented by <u>three</u> parameters: amplitude, phase and angle of arrival, and each sampling antenna provides <u>two</u> measured data points: resultant field strength and resultant phase, the minimum number of sampling antennas must be equal to 3/2, the number of incident plane wave components in order to insure that the number of unknown parameters equals the number of measured data points.

In order for this approach to be valid it is necessary that the incident signal be representable by discrete components. In the present application of the WASS to a landing monitor, the flatness of the runway and its environs will insure that this assumption is valid.

It should be noted that the criterion for roughness is determined by the projected wavelength (free space wavelength divided by the sine of the elevation angle). At L-band and at elevation angles below three degrees the projected wavelength is about 20 feet. Thus, such objects as runway lights, signs, boulders, and other obstructions along the runway or in the region immediately adjacent to the runway should appear "smooth" to the L-band signals from the approaching aircraft. It is therefore reasonable to assume that a typical runway and vicinity will give rise to a well defined reflected component. Drainage slopes and other large scale non-level terrain features will affect only the effective height of the sampling array and can be calibrated out. This will be discussed more fully in Section 5.2.

In principle, the resolving power and the accuracy of the WASS is determined only by the available signal-to-noise ratio.

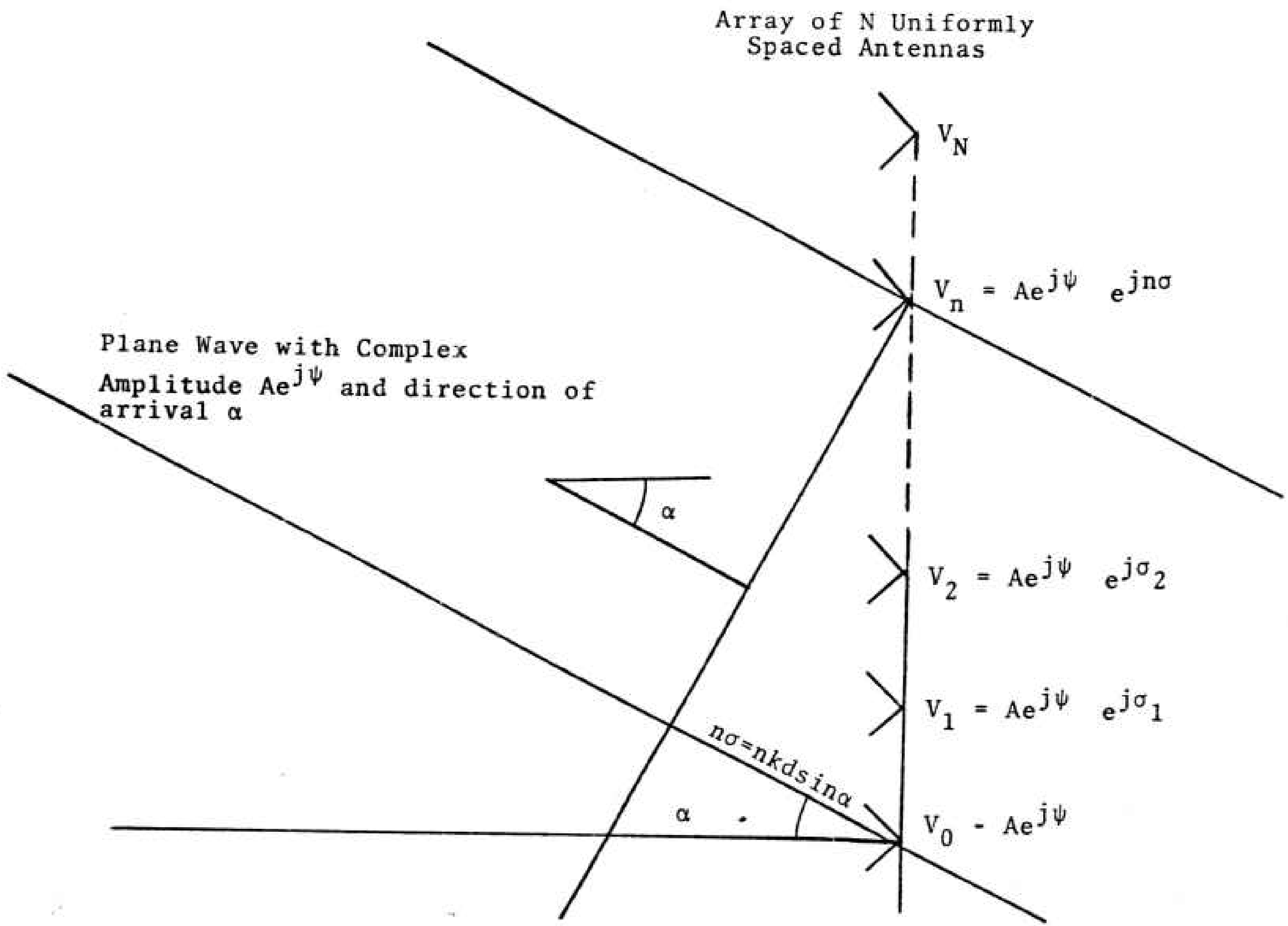


Figure 3-1

Relative Voltage Distribution in a Uniformly Spaced Array Due to a Plane Wave

In a previous RADC sponsored study* it was demonstrated that in order to achieve angular resolutions of one-fifth of the equivalent beamwidth, which would permit tracking of the approaching aircraft to within 25 feet above the ground 7,000 feet from the sampling array, a minimum signal-to-noise ratio will need to be about 30 dB. Signals more than 20 dB in excess of this value can be expected under normal operating conditions. However, it is reasonable to assume that equipment limitations and secondary scattering from minor terrain irregularities will limit the effective signal-to-noise ratio to about 40 dB regardless of the available signal strength. This will insure very good performance of the WASS landing monitor.

3.2 HISTORICAL SUMMARY

The wave sampling technique was first tried in 1966 at the Pacific Missile Range, Point Mugu, to explore the feasibility of separating the multipath components which severely impair performance of the FPS-16 tracking radars at low angles of elevation. This work was performed under Navy Contract No. N123(61756) 56256A.

The experimental antenna was a 12-foot vertical array consisting of six, 9"x12" C-band horns positioned by the side of a 12-foot FPS-16 radar antenna. The test source was located on top of a 90-foot tower on Santa Cruz Island about 30 miles west of Point Mugu. This was also the location of the radar calibrating beacon. The elevation angle from the radar to the beacon was about half a degree.

The receiver was a two-channel, phase-lock receiver. One channel was connected permanently to one of the antennas and the other was sequentially switched among the remaining five antennas. This switching technique proved to be marginal and contributed appreciably to signal degradation.

In spite of various logistical, experimental, and computer programming difficulties, the results were most encouraging. The sea-reflected and direct components were readily separated and identified. Also frequently present was a third component which was presumably associated with the reflection from the inversion layer which is quite prevalent in the coastal regions of Southern California. The conclusion which was drawn as the

*Contract No. F30602-70-C-0290. See RADC Report No. RADC-TR-71-262, November 1971.

result of that study was that the multipath field can be separated into its components and this information utilized to increase the tracking capability of monopulse radars at low angles of elevation.

Shortly after the initial work at Point Mugu was completed in 1967, Rome Air Development Center had a requirement for an improved direction finding technique using troposcatter in the S-band region. A proposal to utilize the Wave Sampling Technique was submitted and accepted. This effort was carried out under RADC Contract No. F30602-68-0157.

In carrying out the RADC study, the experience gained at Point Mugu was invaluable. The experimental setup which was utilized in connection with the RADC program was similar to the one used at Point Mugu, but the details of handling experimental data were much improved.

The antenna array consisted of six, four-foot parabolic reflectors mounted horizontally five feet apart. The axis of the array was approximately broadside to the expected angle of arrival. Each of the six sampling antennas had its own receiver channel, and the data was recorded directly on a digital tape recorder in an IBM-compatible format. The data consisted of two quadrature outputs rather than amplitude and phase separately. This is much simpler and a more accurate technique since it avoids the usual problems of phase meter linearity and discontinuity.

A considerable effort was put into the development of a better mathematical formulation. The end effect was the closed form solution which could be readily generalized to any size of array.

The tests were carried out in November 1968, and the experimental results were most gratifying. The test transmitter was a 3,000 MHz high power pulse transmitter located at Verona, New York. The receiver site was set up on the west side of Lake Canandaigua, about 90 miles west of Verona and well beyond the line-of-sight. A surveying team from Rome Air Development Center carefully located the receiving site and a calibrating source about five miles away. Tests were carried out intermittently over a three-week period and covered a reasonable range of meteorological conditions and diurnal effects. The data was subsequently processed by the GE 635 computer at Rome Air Development Center.

Although only a fraction of all experimental data has been processed by the computer, the part that was processed gave a very clear and convincing demonstration of the effectiveness of

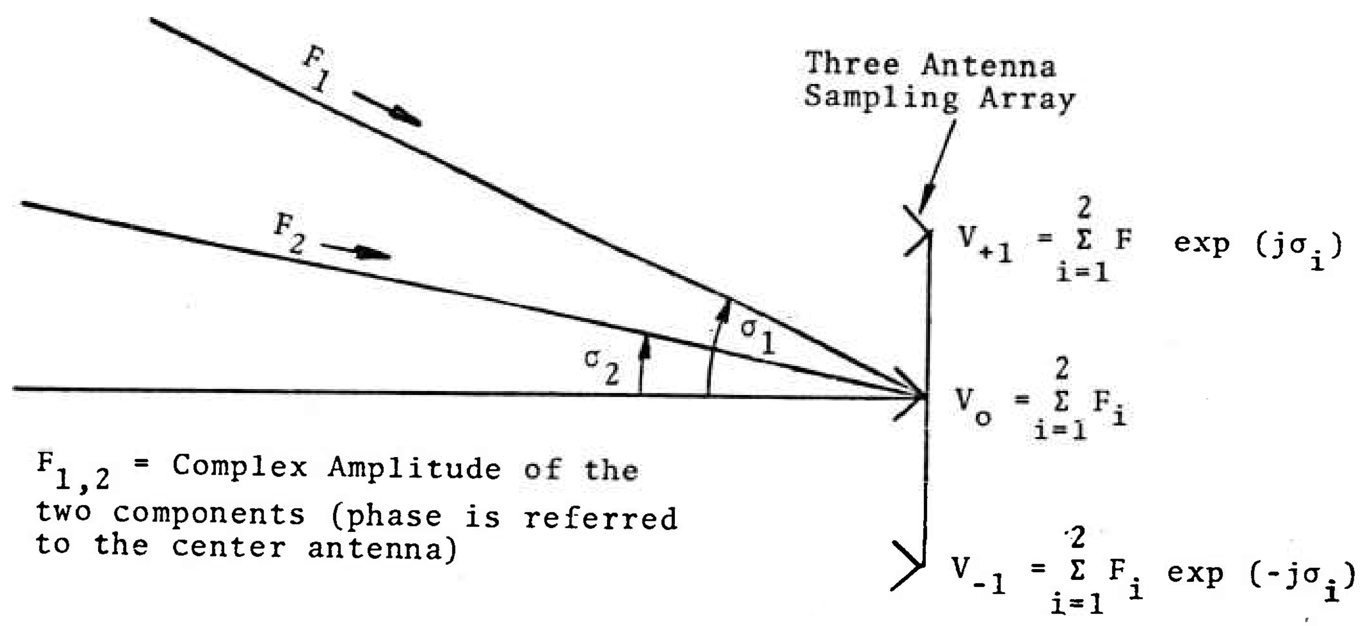


Figure 3-2
Three Antenna - Two Component Geometry

the sampling technique. First, it was shown that the incident scatter field can be adequately represented by no more than four components about 60 percent of the time. These periods lasted for seconds or fractions of seconds at a time, and consequently, for all practical purposes, intervals of time when four-component representation was adequate were nearly always present.

The multipath component associated with the great circle path was almost always present and was frequently the strongest one. The other three components meandered around and when the results were averaged over a number of samples, the distribution of angles of arrival clearly peaked around the great circle path, well within .1° and frequently better than .05°.*

Since a 30-foot array with uniform illumination would have .77° between half-power points, the resolution of the wave sampling technique was shown to be about an order of magnitude better than that which could be obtained with a scanning beam. Some of the experimental data was actually processed at RADC using conventional monopulse tracking programs. The results in general were much poorer.

An analysis of additional data and the development of improved data handling for Spatial Sampling Techniques were carried out under the RADC Contract No. F30602-70-C-0092. This effort further reinforced the above experimental conclusions and provided important information for improved design and calibration procedures for the next generation equipment. This effort also included a fairly extensive error analysis. The results are described in RADC Technical Report RADC-TR-70-88 dated June 1970.

In the Fall of 1970 an effort was undertaken under RADC Contract No. F30602-70-C-0290 to theoretically investigate the applicability of the Wavefront Sampling Technique to various Air Force problems with special reference to GCA. Results of these studies were most gratifying and are described in detail in RADC Technical Report No. TR-71-262 dated November 1971.

A considerable part of the effort was directed toward the analytical aspects of the problem. First, the Wavefront Sampling Theory was extended to include both Spatial and Angular Sampling. Then the theory of sampling was shown to be applicable to noncoherent signals. This extended the range of applicability of

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*In 1973 and 1974 additional data reduction was carried out by Mr. L. Strauss at RADC. The results of this recent analyses confirmed and reinforced the earlier findings and conclusions.

Wavefront Sampling to jammer rejection where there is usually no coherence between the desired and the interfering signal. Another area investigated was the problem of diffused reflection. It was demonstrated that diffused signals will, in general, behave as a multiplicative noise which will determine the maximum achievable signal-to-noise ratio. The problem of nonspecular and specular terrain reflection was considered in some detail. Theoretical models of runways were formulated and computer simulation studies of various effects on the WASS technique were investigated.

One important aspect of the theoretical study was a detailed investigation of errors for the two component, three antenna geometry. Realistic limits of achievable accuracy were formulated in terms of angular separation of the signal components and signal-to-noise ratio. An interesting and important discovery was made that the quality of data can be significantly improved by gating out signals whose measured phase difference is nearly zero or 180 degrees. Furthermore, phase relationships between phases of reflected and direct components can be fairly accurately determined. This carries important implications for landing monitor applications, since such information could be used to help to determine the aircraft height to within a few feet during its final approach up to touchdown.

An extensive computer simulation of two-components multipath geometry typical of an airport environment was carried out. Since the results of this particular investigation have clearly demonstrated the enormous resolving potential of the Wavefront Sampling Technique with special reference to landing monitoring applications, they are briefly described below.

Results of computer simulation can be conveniently expressed in terms of the "Equivalent Half Power Beam Width" (EBW) which is the ratio of the wavelength to the total antenna aperture. Physically, EBW is half the null-to-null beamwidth of a uniformly illuminated antenna aperture of the same size as the sampling array and it is approximately equal to the half-power beamwidths obtainable with that size of antenna aperture using conventional techniques.

It was shown that with a 40 dB signal-to-noise ratio in the processing bandwidth, Wavefront Sampling will resolve two components of comparable magnitude to within .1 EBW with an average error of .01 of EBW. With 30 dB of SNR, the resolving power is better than .2 of EBW with an average accuracy of .01 EBW. Computer simulations have shown that for such applications as landing monitoring a 40 dB SNR in the processing bandwidth should be

readily achievable, particularly as the aircraft is in its final approach to the field.

The highly encouraging computer simulation study was followed by an experimental verification of its key forecasts (RADC Contract No. F30602-72-C-0344). The tests were carried out at 3,000 MHz over a water reservoir to simulate the flat area of the runway and vicinity. The receiving WASS antenna consisted of three, 16-inch horns spaced 42 inches apart and occupying a total aperture of 100 inches. The primary transmitter was a CW source with an effective radiated power of +22 dBm or 160 milliwatts. A secondary transmitter consisting of a laboratory signal generator with effective radiated power of +14 dBm or 25 milliwatts was also used for variable amplitude, CW, and pulse tests. Pulse peak power was the same as CW. Pulse duration was 1 microsecond and pulse repetition rate was 1,000 pulses per second.

The 100-inch receiving antenna aperture, if utilized for a parabolic reflector, would have 2.7° half-power beamwidth. Since the distance across the lake was 736 feet, the 2.7° beamwidth subtended 37 feet. This implied that targets less than about 40 feet apart could not be separated by conventional techniques. Stating it somewhat differently, the target height would have to be 20 feet above the water level and its image 20 feet below the water level before the receiving antenna could separate the two targets. The WASS easily separated the target from its image when the target was as little as one foot above water or .078° elevation angle. The angular separation of the resolved target and its image was .155° which is to be compared with the equivalent aperture beamwidth of 2.7°. The accuracy of the fix was typically .1 foot or .008 degrees.

Most tests were performed in the CW mode with a signal-to-noise ratio somewhat in excess of 40 dB. However, since the receiver was specifically designed to work with ASR radars (S-band, less than 1 microsecond pulsewidth, and pulse repetition rate of about 1,000 per second), the CW signal was sampled over time intervals of less than 1 microsecond and held by the receiver. There was no discernable difference in the system performance between pulsed and CW signals.

The experimental results not only verified but actually exceeded by a substantial margin the encouraging forecasts of the previously carried out computer simulation study.

By far the most important result of the whole study was the clear demonstration that Wavefront Sampling can provide the basis for an extremely accurate and versatile landing monitoring system

as well as a generalized monopulse approach for improved tracking and direction finding capabilities at low angles of elevation.

3.3 REVIEW OF THE WASS THEORY

In this section the basis of WASS equations will be derived. The solution will be specialized to the three antenna two component geometry which is of special interest to the landing monitor application. The general solution has been detailed in the previously referenced RADC report and will not be given here.

3.3.1 THE GENERAL WASS FAR FIELD SOLUTION

Figure 3-1 shows an array of N uniformly spaced antennas illuminated by a plane wave with a complex amplitude of A $\exp(j\psi)$, which will be progressively phase delayed by σ per antenna element.

Clearly, if there are I components comprising the field, then the voltage seen by the n^{th} antenna is

$$V_n = \sum_{i=1}^{I} F \exp(jn\sigma_i) \qquad (1)$$

where

$n = 0, 1, 2 \ldots\ldots N-1$

F_i = complex amplitude

$= A_i \exp(j\psi_i)$

$A_i = |F_i|$

σ_i = normalized angle of arrival

$= (2\pi d/\lambda) \sin \alpha_i$

λ = signal wavelength

d = antenna spacing

The required condition for the equations to be solvable is that the number of unknowns equals the number of independent measured data points, or

$N = 3I/2.$

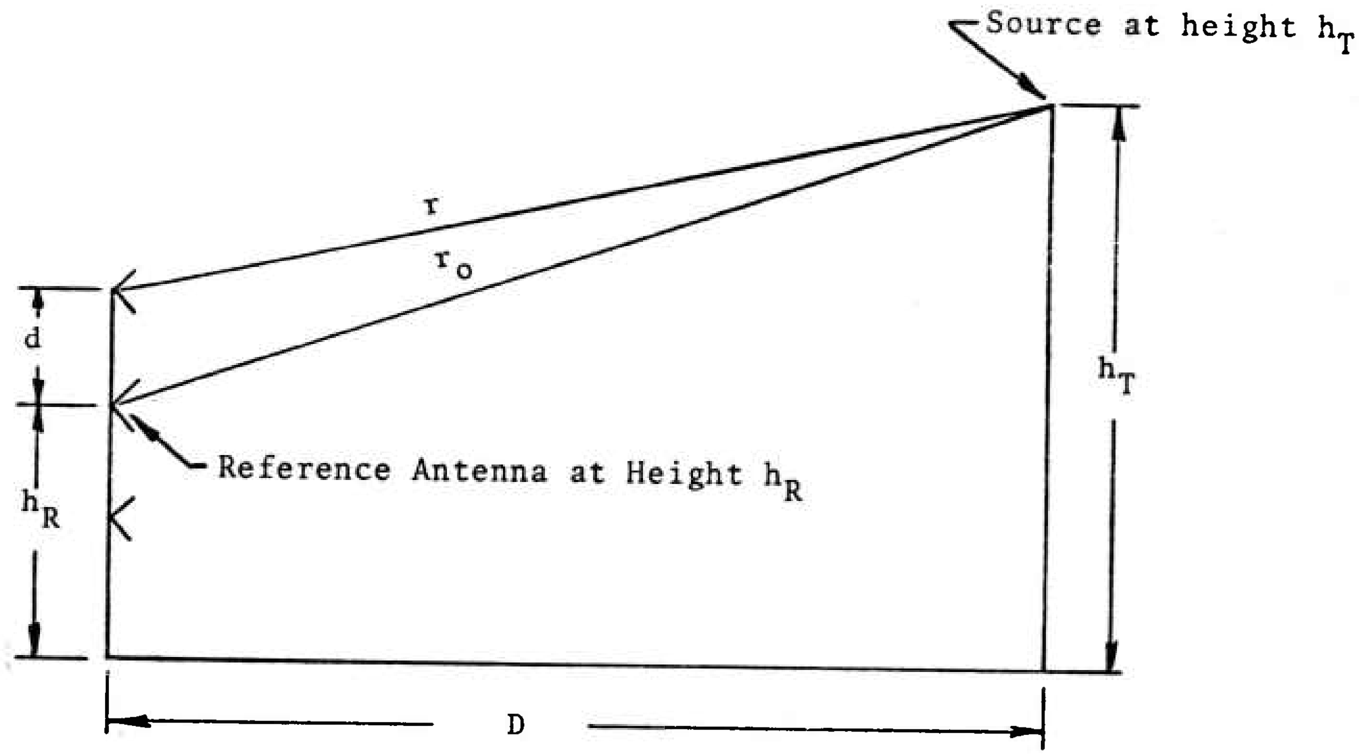

Figure 3-3
Geometry of Spherical Correction

The general solution of these equations is fairly complex and is detailed in the previously referred to RADC report TR-71-262. It will suffice to state that the general solution involves an inversion of two matrices of N-1 order with complex elements and solution of an $I^{\underline{th}}$ order polynominal also with complex coefficients.

If there are less than 2N/3 components, there will be an over-determined set of equations which will result in a singular matrix. Such a condition is handled by the computer by reducing the order of the matrix until a non-singular matrix is obtained. In practice the digital solution will, in general, yield 2N/3 components but the extraneous components which are the result of the system noise or computer roundoff errors are typically tens of dB smaller than the real components and can be readily recognized or ignored.

An alternate and perhaps a more desirable way to handle the over-determined case is to use a least square fit to fewer components. This is a standard technique but it could add a substantial burden to the data processor. Such software modifications can be added at a later date if it turns out to be desirable to do so.

If the number of significant components is greater than 2N/3 then, frequently, the observed antenna voltage cannot be expressed by 2N/3 real components and the computer solution gives complex angles of arrival which, of course, have no physical significance other than to indicate that the assumed number of components is inadequate to describe the incident field.

The converse is not true. Real angle solution does not guarantee that the incident field is made up of only 2N/3 components. In the landing monitor application it is not anticipated that there will be more than two components except for occasional interference from a flock of birds, moving aircraft, and trucks. Tests performed in the course of this study indicated that the presence of a transient third component in a two component solution will usually cause some quasi periodic instability in the angular position of both the direct and the reflected components. This condition can be readily recognized and data could be either averaged out or discarded.

In writing Equation (1), it was tacitly assumed that the sampling antenna beamwidths were broad enough to accommodate all multipath components without further correction for beam shaping. For the purpose of multipath analysis, the only requirement that is placed on sampling antennas is that their angular response be identical. It is for this very reason that it is both possible

and desirable to "filter" the incoming signals using fairly directive antennas and thus minimize the contribution from components way off the direction of arrival of interest. In the present application moderate gain horns will be used.

The discussion so far has been confined to Wavefront Sampling in Spatial Domain where the sampling antennas are distributed along an array, but it is clear from theoretical considerations that analogous results could be obtained with Angular Sampling by using multiple feeds inside of a parabolic reflector or forming multiple beams with a large phased array. The relationship between Spatial and Angular Sampling is analogous to that of phased arrays and reflecting antennas. The theory of Wavefront Angular Sampling is fully discussed in RADC Technical Report TR-71-262. Angular Sampling appears to be somewhat more difficult to implement than the Spatial Sampling (WASS) and it has not been considered for the landing monitor application.

3.3.2 SPECIALIZATION TO THE TWO COMPONENT GEOMETRY

Although (as stated earlier) the general solution of the WASS equations is quite involved, the specialization of this solution to the three-antenna, two-component case is fairly easy and instructive. Furthermore, since this is precisely the case in which we are primarily interested, it will be very worthwhile to develop it in detail since such a development will clearly illustrate the type of problems which a practical WASS landing monitor will be required to handle.

Assume that two plane waves of complex amplitudes $F_i = |F_i| \exp(j\psi_i)$ are incident on a three-element antenna array as shown in Figure 3-2. Equation (1) may be rewritten as

$$V_{+1} = F_1 \exp(+j\sigma_1) + F_2 \exp(+j\sigma_2) \tag{2a}$$

$$V_0 = F_1 + F_2 \tag{2b}$$

$$V_{-1} = F_1 \exp(-j\sigma_1) + F_2 \exp(-j\sigma_2) \tag{2c}$$

where

$\sigma_{1,2} = (2\pi/\lambda) d \sin \alpha_{1,2}$ = normalized angle of arrival

d = spacing between antennas

λ = wavelength

$\alpha_{1,2}$ = angle of arrival

V_i = complex antenna voltage

F_i = complex amplitude = $|F_i| \exp(j\psi_i)$

ψ_i = phase relative to some arbitrary point in space.

For convenience we will define

$$X_{1,2} = \exp(j\sigma_{1,2}).$$

Equation (2) may be rewritten as:

$$V_{+1} = F_1 X_1^{+1} + F_2 X_2^{+1} \tag{3a}$$

$$V_0 = F_1 + F_2 \tag{3b}$$

$$V_{-1} = F_1 X_1^{-1} + F_2 X_2^{-1}. \tag{3c}$$

The problem is to solve for $F_{1,2}$ and $X_{1,2}$ in terms of V_i's. Note that since F_i and V_i are complex, there are six unknowns and six measured values. (X_i is a complex number with the absolute value of one and it is therefore completely specified by one real number σ_i).

To solve Equation (3), we assume that there is a polynomial

$$X^2 + C_1 X + C_2 = 0 \tag{4}$$

whose roots are the X_1 and X_2. (C_1 and C_2 are complex coefficients).

We now rewrite (3) by multiplying by C_i.

$$V_{+1} = F_1 X_1^{-1} (X_1^2) + F_2 X_2^{-1} (X_2^2) \tag{5}$$

$$C_1 V_0 = F_1 X_1^{-1} (C_1 X_1) + F_2 X_2^{-1} (C_1 X_2)$$

$$C_2 V_{-1} = F_1 X_1^{-1} (C_2) + F_2 X_2^{-1} (C_2).$$

We sum vertically to obtain

$$V_{+1} + C_1V_0 + C_2V_{-1} = F_1X_1^{-1}(X_1^2 + C_1X_1 + C_2)$$
$$+ F_2X_2^{-1}(X_2^2 + C_1X_2 + C_2) = 0 \tag{6}$$

since by assumption $X_{1,2}$ are the roots of the polynomial (4).

Inasmuch as Equation (6) is complex and is equal to zero, it follows that its conjugate is also equal to zero. This is necessarily true since in order for a complex expression to be equal to zero, its real and imaginary parts must be independently equal to zero. This obviously is also true for their sum and difference. Thus

$$V^*_{+1} + C^*_1V^*_0 + C^*_2V^*_{-1} = 0. \tag{7}$$

Equations (6) and (7) contain four unknowns C_1, C_2, C^*_1, and C^*_2. Before these equations can be solved for C_1 and C_2 in terms of measured voltages, it will be necessary to express C^*_1 and C^*_2 in terms of C_1 and C_2.

To find relationships between C_i and C^*_i we note that

$$-C_1=X_1+X_2=\exp(j\sigma_1)+\exp(j\sigma_2) = \text{(sum of the roots)}$$
$$C_2=X_1X_2=\exp(j\sigma_1)\ \exp(j\sigma_2)=\text{(product of the roots)}.$$

Thus

$$-C^*_1 = X^*_1 + X^*_2 = 1/X_1 + 1/X_2$$
$$= (X_1 + X_2)/X_1X_2 = -C_1/C_2$$
$$C^*_2 = X^*_1X^*_2 = 1/(X_1X_2) = 1/C_2.$$

The required relationships between C^*_i and C_i are

$$C^*_1 = C_1/C_2 \tag{8a}$$
$$C^*_2 = 1/C_2. \tag{8b}$$

Substitutions in (7) yields

$$(1/C_2)\ V^*_{-1} + (C_1/C_2)\ V^*_0 + V^*_{+1} = 0 \tag{9}$$

which together with (6) leads to the following set of equations:

$$C_2\, V^*_{+1} + C_1 V^*_0 + V^*_{-1} = 0$$
$$C_2\, V_{-1} + C_1\, V_0 + V_{+1} = 0. \tag{10}$$

The above equations can be solved for C_1 in terms of measured voltages,

$$C_1 = (\, V_{-1}{}^2 - V_{+1}{}^2)/(V_0 V^*_{+1} - V^*_0 V_{-1}). \tag{11}$$

We use (8) to express C_2 in terms of C_1 and C^*_1:

$$C_2 = C_1/C^*_1$$

Substituting in (4),

$$C^*_1 X^2 + C_1 C^*_1 X + C_1 = 0$$

$$X_{1,2} = (-a \pm \sqrt{a^2 - 4a}\ )/2C^*_1 \tag{12}$$

where $a = C_1 C^*_1$.

Substituting in (3b) and 3c),.

$$F_1 = (V_{+1} - V_0 V_2)/(X_1 - X_2)$$
$$F_2 = V_0 - F_1. \tag{13}$$

This completes the solution for X_1, X_2, F_1, and F_2 in terms of measured voltages.

To obtain a somewhat better insight into the meaning of the above equations, it will be useful to rewrite (11) as:

$$C_1 = N/D \tag{14}$$

where

$$N = (V_{+1}{}^2 - V_{-1}{}^2)/\ V_0{}^2 \tag{15a}$$

and

$$D = (V_{-1}/V_0)\ - (V_{+1}/V_0)^* \tag{15b}$$

Combining (15) with (3) we get:

$$N = Q(X^*_1 X_2 - X_1 X^*_2) = 2j\ Q\ \sin(\sigma_2 - \sigma_1) \tag{16a}$$

$$D = Q(X_2^*-X_1^*) = Q(\exp(-j\sigma_2)-\exp(-j\sigma_1)) \tag{16b}$$

$$Q = (F_1^*F_2-F_1F_2^*)/\left|F_1+F_2\right|^2 \tag{16c}$$

$$= 2j\ \rho \sin(\psi_2-\psi_1)/(1+\rho^2+2\rho\cos(\psi_2-\psi_1)) \tag{16d}$$

$$\rho = F_2/F_1 \tag{16e}$$

The purpose of the above discussion was to express the quadratic equation coefficient C_1 in terms of the physical parameters of the incident signal. This will allow us to examine conditions under which the WASS solution may fail. Furthermore, it also turns out that the relationships expressed by Equation (16) lend themselves to the development of a simple and an effective flag system which could sense potential problems and initiate appropriate corrective actions.

As explained below, the proposed flag system is based on the monitoring of quantities N and D defined by Equation (15). These quantities can be simply expressed in terms of the measured antenna voltages.

It will be noted that if Q goes to zero, both N and D will approach zero and C_1 will become indeterminate. This condition will occur when $\psi_1 - \psi_2 = n\pi$ and it physically corresponds to the situation where either the maximum or the minimum of the interference pattern is precisely at the phase center of the center antenna. In practice this situation can be avoided by using an array of four or more antennas and using either antennas (1, 2, 3) or (2, 3, 4) etc., whichever yields the larger value of D. In the present application a vertical array of five antennas will be used. This will be described in more detail in Section 7.

If the two angles of arrival approach each other, then both N and D will also approach zero but the absolute value of their ratio will approach 2. This follows immediately from the fact that $C_1 = X_1+X_2 \rightarrow 2$ as $X_1 \rightarrow X_2$. Furthermore, the case of convergence (i.e., single component case) may be recognized by the fact that all sampling antennas will have equal amplitudes and linearly progressive phase shifts. This can be expressed as follows.

$$V_{+1}/V_0 = V_0/V_{-1} \text{ and } \left|V_1\right| = \left|V_0\right| = \left|V_{-1}\right| \tag{17}$$

If and when conditions delineated by Equation (17) are satisfied within limits defined by the available signal-to-noise ratio or some other threshold, the WASS processor will automatically

switch to the single component geometry.

Single component solution is quite simple:

$$F_1 = F_2 = F = |V_0| \tag{18}$$

$$X_1 = X_2 = X = V_1/V_0. \tag{19}$$

There is still a third condition which should be monitored and that is when $C_1 > 2$. The physical interpretation of this is the presence of significant energy from more than two components. Formal solution yields values for X_1 and X_2 which can be satisfied only by complex angles of arrival as seen from Equation (12).

As stated earlier, this condition is not anticipated under normal operation but may happen occasionally due to a reflection from a moving object or an interference from some other transponder in the area which has been interrogated by some other system. Range gating will minimize this problem but, when occasionally it should happen to interfere with a particular data sample, it will be recognized and the data sample will be rejected.

The purpose of the above discussion was to demonstrate the rather unique feature of the WASS technique which lends itself to self monitoring of the incoming data by the use of simple flags.

The above equations have also been solved with an analog processor. Such a processor has been built and has been successfully utilized for real time data reduction. It has been considered as a possible alternative to the digital data processing system but recent developments in the bipolar microprocessors far outstripped possible economic advantages of the analog processor. Furthermore, the processor was subject to d.c. drifts and had to be periodically realigned. While it is possible to circumvent this difficulty it became apparent that digital techniques offer so much more flexibility that analog approach was dropped after a preliminary assessment of possible trade-offs in the early stages of this effort. Further details regarding the analog processor are described in the previously referenced RADC Technical Report.

3.3.3 TWO-COMPONENT RESTRICTED SOLUTION FOR ZERO SLOPE FOREGROUND

It will be instructive to consider a special idealized case of the general WASS solution which leads to a rather simple expression. Let us postulate that we have defined the antenna electric boresight not parallel to the ground but slightly tilted downward so that it intersects the ground directly under the tar-

get. (The target could be the beacon antenna of the approaching aircraft or that of a calibrating source.) For distant targets this is equivalent to the assumption of zero slope antenna foreground.

Under those conditions $\sigma_1 = -\sigma_2 = \sigma$ and Equation (2) may be rewritten as

$$\frac{V_{+1}}{V_0} = \frac{\cos(\psi/2-\sigma) - j\delta \ \sin(\psi/2-\sigma)}{\cos(\psi/2) - j\delta \ \sin(\psi/2)} \tag{24a}$$

where

$$\psi = \psi_2 - \psi_1$$

$$= \text{Relative phase between the two components}$$

and

$$\delta = (1 - \rho)/(1 + \rho)$$

$$\rho = F_1/F_2 \ .$$

Equation (24) can be rewritten as

$$\frac{V_{+1}}{V_0} = \frac{\cos(\psi/2-\sigma)\cos(\psi/2) - \delta^2 \ \sin(\psi/2+\sigma)\sin(\psi/2) - j\delta \ \sin \sigma}{\cos^2(\psi/2) + \delta^2 \ \sin^2 (\psi/2)} \tag{25a}$$

$$\frac{V_{-1}}{V_0} = \frac{\cos(\psi/2+\sigma)\cos(\psi/2) + \delta^2 \ \sin(\psi/2+\sigma)\sin(\psi/2) + j\delta \ \sin \delta}{\cos^2(\psi/2) + \delta^2 \ \sin^2(\psi/2)} \tag{25b}$$

The primary area of interest is when the target is near the ground. Under those conditions the reflection coefficient will be typically almost unity. Estimated values* range from .90 to .95 for targets below 20 milliradians and .95 or higher for targets below 10 milliradians. These values put δ^2 at less than 3×10^{-3} and consequently terms multiplied by δ^2 may be neglected in comparison with the other terms. Equation (25) can thus be approximated by

$$\frac{V_{+1}}{V_0} = \frac{\cos(\psi/2-\sigma)\cos(\psi/2) - j\delta \ \sin \sigma}{\cos^2(\psi/2)} \tag{26a}$$

*See RADC TR-71-262, Page 39.

$$\frac{V_{-1}}{V_0} = \frac{\cos(\psi/2+\sigma)\cos(\psi/2)+j\delta \;\; \sin\sigma}{\cos^2(\psi/2)} \tag{26b}$$

and rather interestingly

$$\frac{V_{+1} + V_{-1}}{V_0} = 2 \cos\sigma \tag{27}$$

The implications of Equations (26) and (27) are rather important.

First, it should be recognized that the slight tilting of the antenna array which was stipulated earlier, simplified equations but did not significantly affect the results. This can be seen from Equation (26). The effect of the tilt, τ, is simply to multiply V_{+1} by $\exp(+j\tau)$ and V_{-1} by $\exp(-j\tau)$. If τ is small, $\exp(\pm j\tau) = 1 \pm j\tau$. Equation (26a) is thus multiplied by $1 + j\tau$ and (26b) by $1 - j\tau$. The net effect on the sum in Equation (27) is to add to the real part a term on the order of $\delta\tau \sin\sigma$ and give rise to an imaginary term on the order of $\tan(\psi/2) \sin\sigma$. For small values of τ and σ these aberrations are negligible, and the results of Equation (27) are valid over the critical area of interest which covers the flare out and the last moments of aircraft flight.

Since it is anticipated that the range to the aircraft will be known from the beacon reply delay, Equation (27) could be rewritten in the form

$$h_T = R \text{ arc cos } [(V_{+1} + V_{-1})/2\, V_0]/kd \tag{28}$$

where

h_T = aircraft height above ground

R = Range to the aircraft

V_i = measured antenna voltage

k = $2\pi/\lambda$

d = spacing between the sampling antennas.

The real significance of Equation (28) is that it indicates

that under fairly reasonable conditions the aircraft height during the last few moments of flight may be calculable by an extremely simple expression involving a multiplication of a constant by the beacon delay and the arc cosine of a ratio of measured antenna voltages.

The field implementation of Equation (28) can be further facilitated by adjusting the reference phase of V_0 to be zero. Since the imaginary parts will then cancel out, only the real parts of the observed voltages will need to be utilized in Equation (28).

Another interesting point which comes out of the examination of Equation (26) is that noise in measured voltages will have a much larger relative effect on the small imaginary term involving δ than on the large real term which determines σ. Consequently it is reasonable to assume that as the signal-to-noise decreases, the relative amplitude information will be degraded but the all-important angular information will remain reasonably unaffected. This has been experimentally confirmed.

The above simplified but restricted two component solution which assumes zero slope in the antenna foreground led to an alternate method for obtaining a general two component solution. The alternate method was developed during the latter part of the current effort and it appears to have a potential for a somewhat faster and a more efficient computer implementation. This is described in the next section.

3.4 ALTERNATE FORMULATION OF THE WASS EQUATIONS

The general solutions of the WASS equations presented in the preceding sections is the method which must be used when there are many antennas and many plane wave components. There are however specialized solutions applicable only to the case of three antennas and two plane wave components. The formulation presented in this section, developed during the course of the present effort, is one of these specialized solutions which has several advantages. Among these advantages are the following. First, the angles of arrival can be determined from the measured voltages using a hand calculator and simple algorithms so that this solution is particularly valuable for monitoring the results of the measurement system in the field when no computer is available. Secondly, this formulation lends itself to computer algorithms which do not require complex arithmetic and might therefore be advantageous in applications where limited computer facilities are available. Thirdly, some of the effects of measurement errors on the deduced arrived angles can be seen in a particularly clear fashion.

To derive this formulation let us rewrite the explicit equations for the fields at three antennas when two plane wave components are present.

$$V_1 = F_1\exp(j\sigma_1)+F_2\exp(j\sigma_2) \tag{29}$$

$$V_0 = F_1+F_2 \tag{30}$$

and

$$V_{-1} = F_1\exp(-j\sigma_1)+F_2\exp(-j\sigma_2). \tag{31}$$

We now make the following substitutions. Let

$$\theta = -(\sigma_1+\sigma_2)/2$$

and

$$\phi = -(\sigma_1-\sigma_2)/2.$$

The antenna voltages then become

$$V_{-1} = \exp(j\theta)\ [F_1\exp(j\phi)+F_2\exp(-j\phi)]$$

$$V_0 = F_1+F_2$$

and

$$V_1 = \exp(-j\theta)\ [F_1\exp(-j\phi)+F_2\exp(j\phi)]$$

From these equations we have

$$V_{-1}\exp(-j\theta)+V_1\exp(j\theta) = 2V_0\cos(\phi)$$

Defining

$$\bar{V}_{-1} = V_{-1}/V_2 = R_{-1}+jI_{-1} \tag{32}$$

and

$$\bar{V}_1 = V_1/V_2 = R_1+jI_1 \tag{33}$$

the solutions for θ, ϕ, and the normalized arrival angles are

$$\tan\theta = (I_{-1}+I_1)/(R_1-R_{-1}) \tag{34}$$

$$\cos\phi = [(R_1+R_{-1})\cos\theta+(I_{-1}-I_1)\sin\theta]/2 \tag{35}$$

$$\sigma_1 = -\theta-\phi \tag{36}$$

and

$$\sigma_2 = -\theta+\phi. \tag{37}$$

The ratio of the plane wave amplitudes and the relative phase of the plane waves measured at the center antenna (antenna 0) are given by several different expressions. One set is

$$A_1^2/A_2^2 = (X_2^2 + Z^2)/(X_1^2 + Z^2)$$

$$\psi_1-\psi_2 = \pi + \text{arc tan } (Z/X_2)-\text{arc tan } (Z/X_1)$$

where

$$X_1 = R_{-1}+R_1-2\cos\sigma_1$$

$$X_2 = R_{-1}+R_1-2\cos\sigma_2$$

and

$$Z = I_{-1}+I_1$$

A second set is

$$A_1^2/A_2^2 = (Z_2^2 + Y_2^2)/(Z_2^2 + Y_1^2)$$

$$\psi_1-\psi_2 = \pi + \text{arc tan } (Y_2/Z_2)-\text{arc tan } (Y_1/Z_2)$$

where

$$Y_1 = I_{-1}-I_1+2\sin\sigma_1$$

$$Y_2 = I_{-1}-I_1+2\sin\sigma_2$$

and

$$Z_2 = R_{-1}-R_1.$$

The second of these sets should be the more useful of the two in the runway geometry where $\sigma_1 \approx -\sigma_2$.

To complete the solution involving only real arithmetic we

assume that the input data is in the form of amplitude and phase. That is,

$$V_n = v_n \exp(jP_n). \tag{40}$$

$$R_{-1} = (v_{-1}/v_0) \cos (P_{-1}-P_0) \tag{41}$$

$$I_{-1} = (v_{-1}/v_0) \sin (P_{-1}-P_0) \tag{42}$$

with corresponding expressions for R_1 and I_1.

3.5 SPHERICAL CORRECTION

In deriving the WASS equations it was assumed that the incident signal consisted of plane waves. While this assumption is well justified for sources far away, it will lead to a measurable error when the source is close. For instance, spherical aberration for a 16-foot antenna aperture and a target distance of 6,000 feet will result in about 3° maximum phase error at L-band. While this error is not large, it may affect the accuracy for targets less than 10,000 feet unless a simple correction is made.

The derivation of the correction is illustrated in Figure 3-3. Let r_o be the distance from the phase center of the receiving array to the source at height h_T and r be the distance to the source from the sampling antenna displaced by d from the phase center. If h_R is the height above ground of the phase center of the receiving array and D is the ground distance between the transmitter and the receiver it follows that

$$r^2 = (h_T - h_R - d)^2 + D^2, \tag{43}$$

$$r_o^2 = (h_T - h_R)^2 + D^2, \tag{44}$$

$$r^2 - r_o^2 = d^2 - 2d(h_T - h_R), \tag{45}$$

but since $r_o \approx r$

$$r - r_o = \frac{r^2 - r_o^2}{r + r_o} \approx \frac{r^2 - r_o^2}{2r_1} = \frac{d^2}{2r_o} - d \sin \alpha, \tag{46}$$

where

$$\sin \alpha = \frac{h_T - h_R}{r_o}$$

= elevation angle of the source.

The total phase difference σ' is given by

$$\sigma' = kd^2/2r_o + kd \sin \alpha \qquad (47)$$

where $k = 2\pi$ /wavelength.

Comparison of Equation (47) with Equation (2) shows that the only difference between the "near range" normalized angle of arrival σ' and the "plane wave" normalized angle of arrival σ is the additional term of $kd^2/2r_o$. This term depends only on the range to the target and goes to zero for large distances. As can be seen from Equation (47), the effect of spherical aberration when inserted in Equation (2) is to multiply both F_1 and F_2 by $\exp(+jkd^2/2r_o)$ in Equation (2a) and also in Equation (2c). No correction is made to Equation (2b) since it is the reference antenna and d = 0.

The corrected version of Equation (2) can be brought back into the standard form simply by replacing V_{+1} by $V_{+1} \exp(-jkd^2/2r_o)$ and V_{-1} by $V_{-1} \exp(-jkd^2/2r_o)$. In other words, the effect of spherical aberration is to cause a small phase shift which is a function of the range to the target (and its image) and the distance of the sampling antenna from the phase center of the array.

The spherical correction will be especially important when the large antenna spacings (see Section 7) will be utilized for monitoring the final portion of the aircraft flight. Since it is such a simple correction it will be automatically incorporated into the data processing software.

3.6 FREE SPACE INTERFEROMETER EQUIVALENCE FEATURE

The WASS receiving array has its image in the ground which "sees" the straight extension of the reflected component. Clearly, if it were possible to connect directly to this image and measure the phase difference between the phase center of the real antenna and its image, then one would have a free space interferometer whose baseline is twice the height of the phase center of

the receiving antenna.

In the presence of a well-defined ground plane such as will normally be encountered in the immediate vicinity of runways, the measured phase difference between the direct and the reflected component as given by the WASS solution is precisely the phase angle one would measure with the free space interferometer described above, modified by a known or a calibrated phase change caused by reflection. For near grazing incidence this phase change on reflection will be very nearly 180°. The departures from 180° could be easily calculated from the known dielectric properties of the surrounding reflecting area.

This technique was applied in the over-water experiments described in the previously referenced RADC report and the results were excellent. A possible complication in applying the free space interferometer feature to the WASS in the field is the fact that in most cases the surrounding ground will not be as level as the water surface but will have certain small tilts and humps which may cause shifts in the effective length of the interferometer baseline. Such errors, however, will in general be small, and furthermore should be easily calibratible. This would be a one-time calibration as a function of the angle of arrival and possibly also of the aircraft range at short ranges, where the angle of arrival as seen from the real antenna and its image are significantly different.

A more serious obstacle to the utilization of this feature is the potential uncertainty in the changes of the dielectric properties of the runway and vicinity due to precipitation such as rain and snow. Studies carried out in the course of this effort indicate that these effects can be substantial. This is discussed in more detail in Section 5. It should be emphasized that the Free Space Interferometer Feature is an extra capability which should be available a substantial part of the time. Its presence or absence will have no bearing on the normal WASS operation.

SECTION IV

GENERAL DESCRIPTION OF THE WASS LANDING MONITOR

4.1 GENERAL OVERVIEW

Before proceeding with the detailed description of the WASS Landing Monitor, it will be useful to describe a general overview of how the system is currently envisioned to operate.

Figure 4-1 shows a schematic pictorial of the type of operation which would involve the WASS Landing Monitor. As the aircraft makes its final approach and as it becomes approximately aligned with the runway, the WASS array will initiate the tracking of the aircraft. Typically, this will occur when the aircraft is 5 to 10 miles away from the runway and below 5,000 feet. When the aircraft is sufficiently high, the WASS tracking array will track the aircraft in the normal monopulse mode. However, as the aircraft approaches the ground, the ground-reflected component will make itself felt by presenting a non-uniform wave across the WASS antenna aperture. When this occurs the processing mode of the WASS data will automatically switch from monopulse to wavefront analysis. In this mode the WASS should be capable of tracking the aircraft to within 30 feet above the ground at which time the aircraft will be well over the threshold and should see the runway lights even under very bad weather conditions. The accuracy of position of aircraft is expected to be ± 2 feet in height and ± 100 feet in range.

As the aircraft is being tracked three of the five antennas in the WASS array will transmit interrogation pulses to the aircraft. This pulse will activate a calibrated beacon 500 to 1,000 feet in front of the array, and the transponder aboard the aircraft. Inasmuch as the calibration beacon will be much closer than the aircraft and will not have any appreciable built in delay, the reply from the calibrating beacon should arrive a few microseconds before the beacon reply from the aircraft. The calibrating beacon will be approximately in line with the expected direction of arrival of the aircraft, it will present to the WASS antenna array a wavefront of known amplitude and known phase distribution which will automatically provide instantaneous information on the antenna sway due to wind. Temperature changes and aging which might cause small phase and amplitude drifts in the interchannel tracking of the WASS receiver will be calibrated through the injection of known signals into the antenna elements by means of directional couplers or switches. This will be discussed in more detail later on.

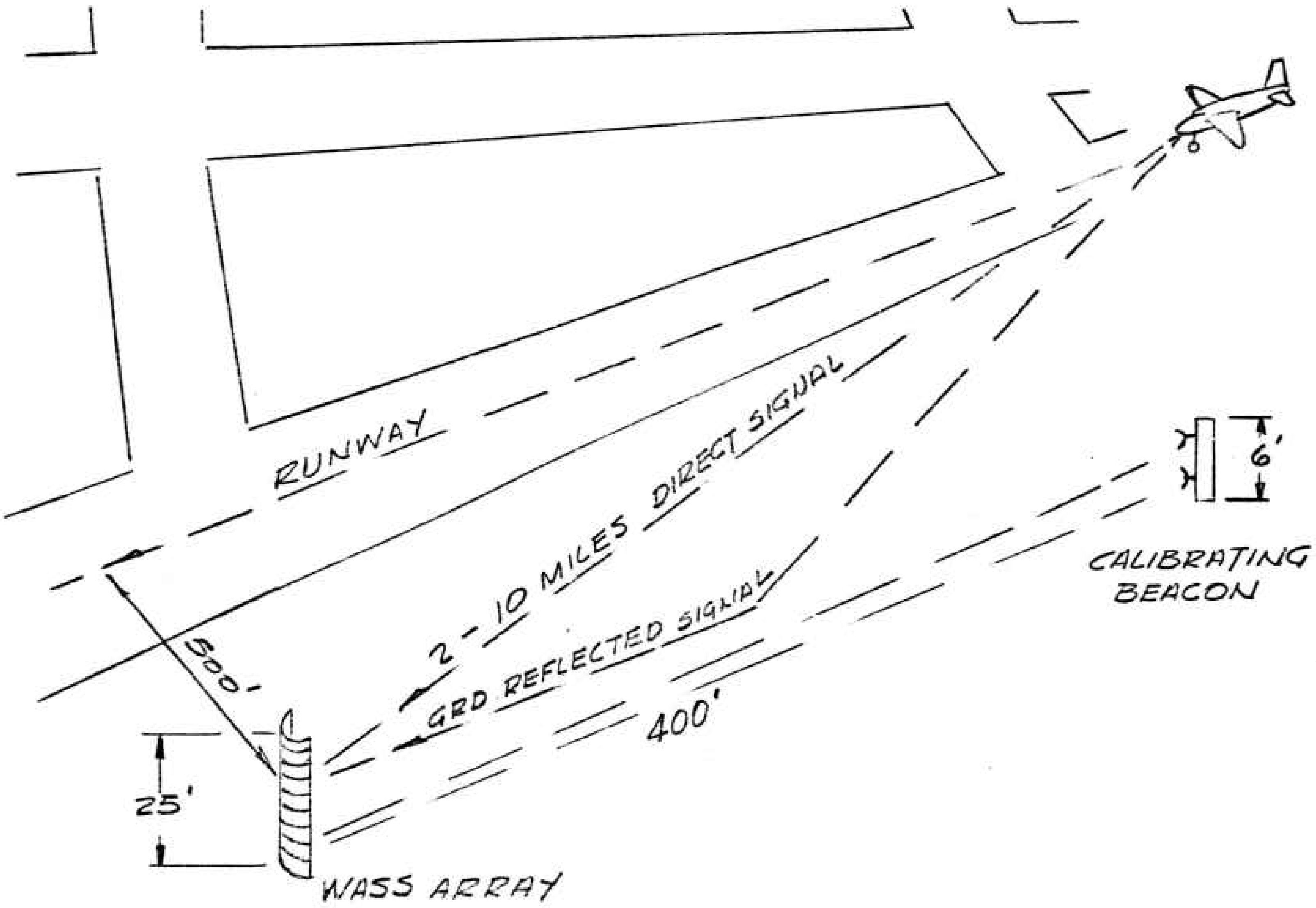

FIGURE 4-1
SCHEMATIC DIAGRAM OF WASS LANDING MONITOR

In tracking the aircraft the WASS is only capable of measur-ing the angle of arrival. To translate this angle of arrival into elevation it is necessary to know the range of the aircraft. For the purpose of this report, it will be assumed that the test air-craft will be equipped with a calibrated transponder delay so that the range can be accurately determined. In looking further ahead, into operational environment, it will be necessary to pro-vide range information by other methods, since many of the older aircraft are not equipped with calibrated transponders. For this purpose, at least two different methods will be available. One utilizes the current precision approach radars which are capable of providing accurate range and azimuth information. The second would make use of a wide base horizontal interferometer consisting of multiple elements separated by several thousand feet. Such triangulation will provide very accurate azimuth and ranging in-formation at the time when it is most needed as the aircraft ap-proaches the runway. For the purpose of the current effort no attempt will be made to provide methods to obtain auxiliary range information or azimuth information since it will be assumed that currently available techniques are very adequate and consequently the thrust of the effort will be directed toward the acquisition of accurate elevation angle information which is very difficult in a multipath environment.

4.2 MAJOR EQUIPMENT SUB-UNITS

The WASS landing monitor can be sub-divided into six major sub-units as shown in Figure 4-2. These are the WASS antenna ar-ray and front end, WASS receiver mainframe, data processor, air-craft and calibrating beacon, interrogating transmitter, interro-gating and ranging unit and data display. A detailed description of these units is given in later sections of this report, but for the purpose of this discussion a brief overview will be presented below.

The WASS antenna consists of a five element vertical array. It was pointed out in an earlier section, that a minimum of three antennas are required to separate the direct and reflected compo-nents. However, in order to avoid blind spots and conditions where the aircraft signature may be lost when the maxima and the minima of the interference patterns are at the center of the an-tenna triplet, it is necessary to provide additional antenna ele-ments. For optimum deployment these elements are not uniformly spaced, but are arranged in such a way that at no time the maxi-mum or the minimum of the interference pattern will be precisely at centers of all triplets within the array. In the preliminary effort no special attempt will be made to provide azimuth mono-pulse operation. However, in the operational environment a double

array of antennas will be utilized to give both azimuth and the elevation angles.

All of the WASS sampling antennas will feed into matched mixers, and will be heterodyned down with a common local oscillator to 60 MHz IF. The 60 MHz IF will then be fed into the WASS receiver frame where it will be processed. In order to avoid possible contamination from multipath other than that from the immediate foreground reflection, only the first framing pulse of the aircraft transponder reply will be utilized. As mentioned in the previous subsection, the sequence of events will be as follows. The interrogating and ranging unit will initiate a pulse which will be transmitted to the aircraft on the 1.03 GHz frequency. This interrogation pulse will also trigger a calibrating beacon a short distance from the WASS array. The reply from the calibrating beacon will enter the WASS antenna array, will pass through the WASS receiver, and will be stored by sample-and-hold circuits in the data processing unit. A moment later the aircraft reply will arrive. It, too, will pass through the WASS antenna array, WASS receiver, and be stored on another set of sample-and-hold circuits in the data processor. As stated earlier, only the leading edge of each of the incoming pulses will be utilized to insure that no contamination other than multipath from the immediate foreground is received. The data processor unit will then digitize the information held by sample-and-hold circuits and will process it through the computer and subsequently display it on the data display unit. A more detailed description of the various functions will be given later on.

4.3 INTERFACE WITH GCA AND ILS FUNCTIONS

In the operational requirements it will be necessary to interface with various GCA and ILS functions. This will be especially important since the WASS system will depend on other sources of range information. Furthermore, the WASS landing monitor will normally not track the aircraft until it is approximately lined up with the runway. In order to insure continuous tracking information the handover functions from the GCA and ATCRBS facilities to WASS will have to be carried out automatically. Conversely the WASS derived information will have to be sent and compatibly displayed to the controller so that appropriate action can be taken. It is also perfectly feasible to uplink the WASS derived information directly to the aircraft through normal VHF channels. This would be especially important in future systems when in the final stages of the approach there is insufficient time for the information to be first sent to the controller and then be re-transmitted by voice to the incoming aircraft.

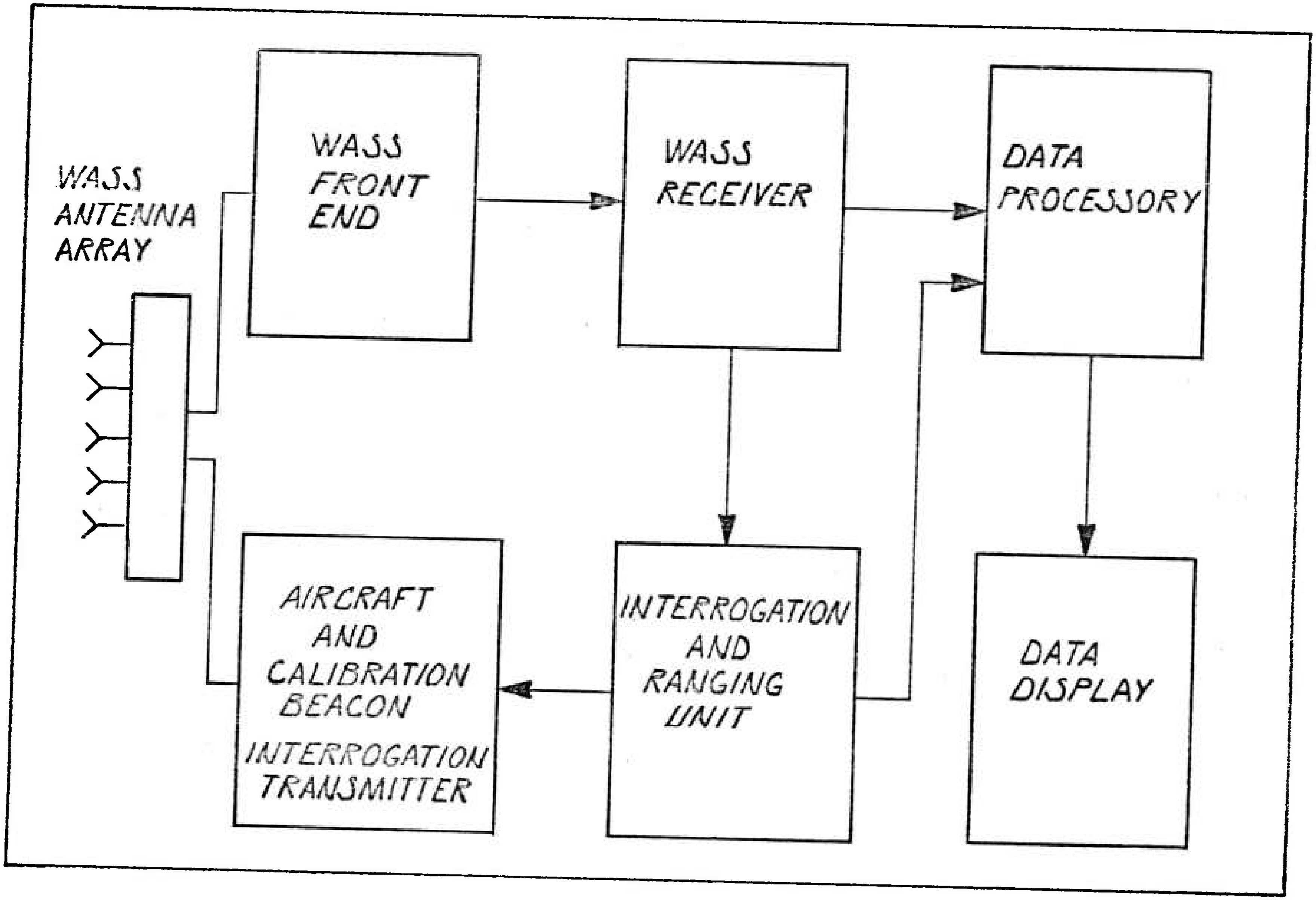

FIGURE 4-2. MAJOR WASS LANDING MONITOR SUBSYSTEMS

Inasmuch as the present effort was directed toward the feasibility evaluation, it was felt that a detailed consideration of the interface would be outside the scope of this effort, and the main emphasis has been placed in the areas where essential features of the WASS technique could be demonstrated and evaluated.

4.4 CALIBRATION

As a result of previous efforts, it became quite apparent that the successful operation of the WASS technique will require the capability to accurately calibrate the WASS antenna array and receivers. It is very difficult, if not impossible, within the present state-of-the-art to construct multichannel radio receiving equipment which will not be subject to small interchannel drifts in gain or phase over a large dynamic range. Since the WASS receiver is a multiple unit receiver it became of paramount importance to provide some means by which the small drifts could be corrected in real time. Also, in order to avoid constructing non-frangible antenna towers it is necessary to provide a real time correction capability for such effects as the wind sway, and solar heating of the interconnecting cables to the antenna and mixer. An easy way to accomplish the wind correction is to place a beacon 500 to 1,000 feet at the antenna foreground. Since the beacon will be close to the ground and will be always in the same position, the relative amplitude and phase of the beacon signal as observed by the WASS sampling antennas can be calculated and compared with measured values. Any departures from that can be attributed to either temperature drift or antenna sway due to the wind. The temperature and other slow drifts will be calibrated out through injection of a known calibrating signal through the directional couplers or switches at the feed terminals of each of the sampling antennas. It is a relatively simple matter to make these corrections and incorporate them in the computer software.

In addition to the real time calibration, it will be necessary to provide a manual or semi-manual capability to check for long time constant effects such as aging, and occasional malfunctions. These effects may cause errors in the quadrature relationship in the coherent detector as well and generate offsets which could cause serious errors which are not normally detectable through routine calibration. These effects are best handled by injection of test signals into various points into the WASS mainframe and will be described in detail later on.

SECTION V
ENVIRONMENTAL CONSIDERATIONS

5.1 SITE SELECTION CRITERIA

The site selection is very important for a successful operation of the WASS landing monitor. The WASS theory requires that the antenna foreground be sufficiently smooth to provide a well defined ground reflection. Interference from nearby objects could cause a severe degradation in the system performance. Normally, however, a judicious choice of site for the WASS antenna should solve most of the problems. It will be important to place the antenna array on the opposite side of that used for taxiing by the incoming and outgoing aircraft. Also, the site should be selected in such a way as to insure that there are no other structures such as antennas, equipment shelter, landing lights, etc. in the immediate vicinity of the WASS array. In trying to assess the relative importance of possible contributions to the WASS signal it should be remembered that most of the reflected energy will come from the first Fresnel zone and objects which are far away outside of that region are not likely to contribute appreciably. The width of the first Fresnel zone will be typically less than 100 feet. The length of the Fresnel zone will be considerably longer, on the order of 3,000 feet, depending upon the elevation angle to the aircraft. It should also be remembered that objects far off to one side will not contribute to the WASS signal since they will be range gated out by the equipment.

5.2 EFFECTS OF RUNWAY TOPOGRAPHY

In general, the runway is not likely to be perfectly level, but will follow local contours, and will also have artificial slopes to accommodate drainage. These departures from perfect level can be as much as 10 feet per thousand.* As long as these slopes are very gradual there will be no noticeable effect on the performance of the normal WASS system. The main effect will be in the utilization of the free space interferometer feature of the WASS technique. The local departure of the slope from zero to some other value will shift the effective boresight and will result in erroneous interpretation of the free space interferometer data. These effects, fortunately, can be easily corrected by a one time calibration using an airborne transmitter.

In the course of this study it has been found that effects

*The Air Force Document AFM 86-8 " Airfield and Airspace Criteria" dated 10 November 1964 specifies maximum longitudinal grades of runways and shoulders of 1% and the rate of change in the slope of .167% per 100 feet or changes in slope of 1 foot per 600 feet of runway.

of moisture on the pavement and on the ground are likely to cause much more serious and largely unpredictable effects on the phase of the ground reflected component and consequently it is now not clear whether or not the free space interferometer feature could be effectively utilized in the routine fashion for tracking the incoming aircraft. This will not affect the normal WASS operation, but it may prevent the utilization of the free space interferometer. Effects of moisture on the reflected component are discussed in Section 5.3.

5.3 EFFECTS OF PRECIPITATION ON FOREGROUND REFLECTION

The reflection coefficients for various types and amounts of precipitation covering an asphalt surface at L-band as a function of elevation angle are plotted in Figure 5-1. From these curves it is quite apparent that the reflection coefficient is significantly changed when even minor amounts of precipitation are present. Since the WASS solution makes no assumptions as to the relative amplitudes and phases of the two plane wave components no direct error would be caused by a uniform precipitation layer on top of the terrain in the antenna foreground. This does not however imply that precipitation effects may be safely ignored as indirect errors can be caused by these changes in the foreground reflection coefficients. These indirect errors will occur through the effects of faulty assumptions about the reflection coefficients in performing system calibrations. This factor is discussed in some detail in Section 6.1 of this report.

In addition to its effects on the real time system calibration, precipitation on the foreground could affect other aspects of the total system. One of these would be a modification of the vertical pattern of the beacon interrogation antenna. This would only be serious if it caused deep nulls in the elevation range where interrogation is desired. For the system described in this report such nulls will not occur no matter what the foreground reflection coefficient is.

Before leaving this subject it should be noted that similar, but generally much smaller, effects would be observed with horizontal polarization. An exception to this is a cover of snow. The dielectric constant of snow is intermediate between that of air and that of asphalt (or most types of dry soil as well as concrete). Consequently, a layer of snow tends to match this substrate to the air and when the combination of snow layer thickness and incidence angle are correct the reflection coefficient becomes virtually zero.

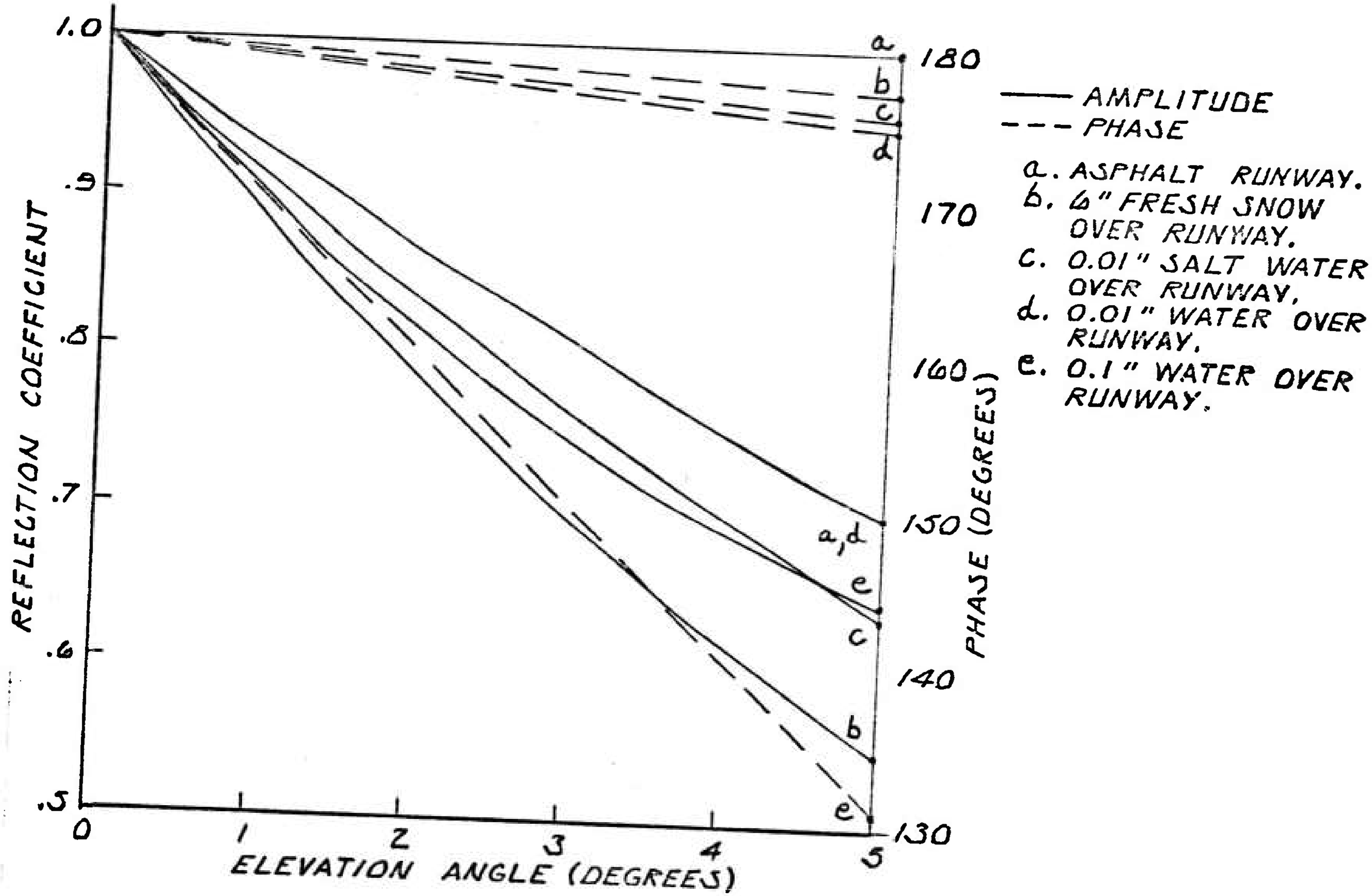

FIGURE 5-1 EFFECTS OF PRECIPITATION ON FOREGROUND REFLECTION COEFFICIENTS VERTICAL POLARIZATION, 1.09 GHZ.

SECTION VI
SYSTEM CALIBRATION

6.1 SYSTEM CALIBRATION PROCEDURES

The WASS system requires a high degree of measurement accuracy. Consequently, relatively frequent system calibrations are required. These calibrations should be performed automatically by the system itself. Two general types of calibration are indicated. These can be generally classified as internal and external. The internal calibration procedure consists of injecting a programmed internally generated signal at RF into the receiver channels and measuring the receiver outputs. This internal calibration procedure serves to define the relative channel gains (in amplitude and phase) and the relative gains and offsets in the detector and A-D converter circuits. The internal calibration procedure needs to be repeated at frequent enough intervals to allow the computer to compensate for such factors as thermal drift. The external calibration procedure consists of programmed transmissions from one or more reference sources located at known positions. The primary purpose of the external calibration is to provide real time definition of the array orientation (i.e., define the system boresight direction) and is therefore required on virtually a pulse by pulse basis. The use of the external calibration will permit the construction of a frangible structure for the WASS antenna array since wind sway correction can be made a few microseconds prior to the reception of the aircraft reply. A secondary purpose of the external calibration is to provide a complete system alignment including some of the same factors tested by the internal calibration as well as the antennas and the RF channels up to the point where the internal calibration signal is inserted. This secondary purpose of the external calibration requires a more refined procedure than the primary purpose but is not needed nearly as frequently. In the following paragraphs the external and internal calibration procedures will be described in more detail.

6.2 EXTERNAL CALIBRATION PROCEDURE

The purpose of the external calibration is to present known fields to the antennas. This is done by transmitting from one or more sources at known locations. As noted above, the external calibration serves two purposes. These two functions are described separately below.

The primary purpose is to define the moment by moment orientaion of the baseline. In order to do this a single source is required which transmits pulses interleaved with the pulses from

the target aircraft. Any change in the orientation of the baseline will cause changes in the relative phases of the voltages of the signals received at the various antennas. As long as the parameters do not vary, the change in the relative phase between two antenna voltages will be proportional to the product of the spacing between the antennas and the baseline deflection angle. Thus, on a short time scale, changes in the orientation of the baseline are defined by changes in the relative phases measured when the external calibration signal is received. The interrogation of the external calibration beacon must clearly be frequent enough to follow the bending of the baseline. This differential baseline calibration must be supplemented by an absolute baseline calibration at periodic intervals. This absolute baseline calibration is required because changes in the reflection coefficient of the ground will also cause changes in the relative phases of the antenna voltages and, when interpreted as baseline changes, will lead to an error in the assumed baseline orientation.

It is planned that the external calibration will be accomplished every time the incoming aircraft is interrogated to provide precise correction for the wind sway. Since the calibration transponder will be located 500 to 1,000 feet in front of the WASS array the reply from the transponder will reach the receiver several microseconds before the reply from the aircraft. The calibrating transponder reply will be a simple pulse about one microsecond duration and will therefore not be accepted by standard transponder receivers as a legitimate aircraft transponder reply.

Calibration of the absolute baseline orientation requires a more sophisticated set of measurements, especially if there is uncertainty in the reflection coefficient of the ground. The calibration of the absolute baseline orientation requires the reception of known fields at the antennas. This can be accomplished by transmitting from known locations and computing the total received field at each antenna in the receiving array. Since the total field consists of a direct wave and a ground reflected wave, the amplitude and phase of the reflected signal must be accurately known. This in turn requires a good knowledge of the ground reflection coefficient. There are at least three possible methods of insuring that the ground reflection coefficients are sufficiently well known. The first of these is to use very large transmitting antennas (narrow beamwidth) and configure the path geometry such that the ground illumination is so small that the reflected wave is not significant. This does not appear to be feasible as the resultant geometry would place a very tight tolerance on the degree to which the patterns of the transmitting and receiving antennas would have to be known. The second possibility is to tailor the ground plane so that its properties are very pre-

cisely known. A possibility along these lines would be to use an elevated wire screen. By making the mesh sufficiently small (1 inch or less) it would have the reflecting properties of a conducting sheet and its properties would not change substantially in rain as there would be no possibility of a sheet of water forming. Ice coating the grid or snow build up could cause problems. Electrically heating the wire grid might be used to solve these difficulties but would clearly decrease the attractiveness of this approach. The third possibility is to treat the ground reflection coefficients as additional variables to be calibrated out. In order to obtain a sufficient number of measurements it would be necessary to use at least two transmitting antenna positions.

The use of multiple transmitting antennas to remove the reflection coefficient uncertainties may be done in the following fashion. Consider the geometry shown in Figure 6-1 where three receiving antennas and two transmitting antennas are shown. The voltage measured at the i'th antenna (i = 1,2,3) when the j'th transmitting antenna is used (j = 1,2) is V_{ij} where

$$V_{ij} = A_i B_j [\exp(j\sigma_{ij}) + R_{ij}\exp(j\sigma'_{ij})]$$

The complex numbers A_i are the complex calibration factors for the i'th antenna. It is the determination of these quantities which is the purpose of the calibration. These complex numbers introduce four unknowns since any one of the A_i may be taken arbitrarily as unity. The complex numbers B_j are unknowns and are introduced in order to account for differences in the amplitude and phase of the transmitted fields from the two transmitting antenna positions as well as the changes in receiver AGC and phase reference when the composite incident field structure is changed. These numbers introduce four additional unknowns. The quantities σ_{ij} and σ'_{ij} are determined solely by geometry and may be assumed known. By reference to Figure 5-1 of Section 5.3 we see that both the amplitude and phase of the reflection coefficients may be represented by linear functions of the incidence angle over reasonable angle ranges. Consequently we express the reflection coefficients R_{ij} by

$$R_{ij} \approx (\rho + a\psi_{ij})\exp[j(\phi + b\psi_{ij})]$$

where the quantities ρ, a, ϕ, and b are unknowns defining the reflection coefficients and the incidence angles ψ_{ij} are determined solely by the geometry and are therefore known. Summarizing then,

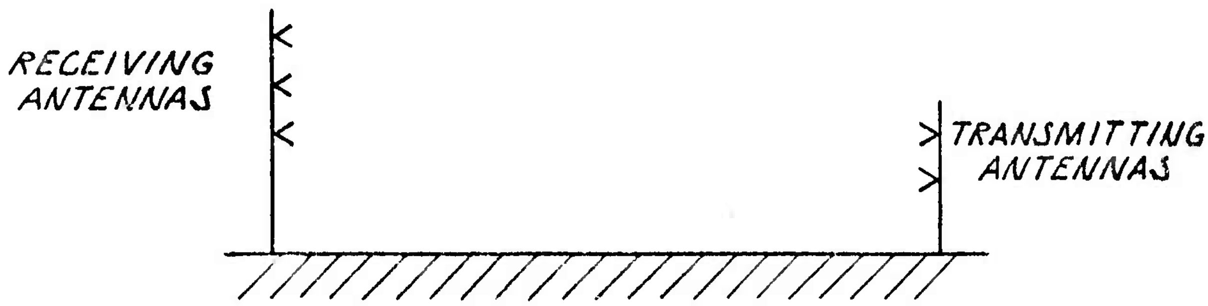

FIGURE 6-1 CALIBRATION TECHNIQUE TO REMOVE UNCERTAINTIES IN GROUND REFLECTION COEFFICENT.

we have 12 unknowns and 12 equations (6 complex equations) from which they may be determined. The two additional antennas present in the array introduce four additional unknowns and eight additional equations leading to an overdetermined solution. This overdetermined solution can be used to minimize the errors in the derived quantities due to small measurement errors and thus increase the confidence in the solutions.

The calibration sources should be located such that both the direct and reflected signals are well within the vertical 3 dB beamwidth of the array elements. It is also desirable that the calibration source heights be chosen so as to avoid placing the minimum of the vertical interference pattern near the center of the array. These requirements may be met by placing the two antennas at heights of 4 and 6 feet approximately 400 feet from the array. For this configuration, the incidence angle at the ground for the various antenna combinations will vary from about 2.5 to about 5.5 degrees.

6.3 INTERNAL CALIBRATION PROCEDURES

The internal calibration is designed to remove receiver generated errors from the data. These errors result from such factors as phase and gain mistracking between receiver channels, zero offsets in the D.C. data channels (post detection), coherent detector gain variations, etc. A typical set of in-phase and quadrature outputs (C and S) for one of the receiver channels can be written as

$$C = A\,\alpha_c V_o \cos(\phi_o + \phi) + \delta_c$$

and

$$S = A\,\alpha_s V_o \sin(\phi_o + \phi) + \delta_s$$

where

A and ϕ are the channel gain and phase errors respectively, V_o and ϕ_o are the "true" amplitude and phase for the channel, α_c and α_s are the coherent detector gains for the in-phase and quadrature detectors respectively and δ_c and δ_s are the coherent detector zero signal offsets (present in any D.C. system). Without loss of generality, amplitude and zero offsets in the A-D converter can be included in the errors already introduced. The channel gain and phase errors may be, and usually are, functions of the AGC control voltage.

In order to determine the six error parameters so that the voltages fed to the computer can be corrected in the computer the following procedure is recommended. A locally generated signal is inserted into the RF channel from each antenna. This insertion can be done either through the use of directional couplers or through electronic switches. The latter procedure is the recommended one as it simultaneously blocks any external signal entering via the antennas.

During part of the period when the internal calibration signal is on the phase of the reference signal for the coherent detectors is varied through a 360 degree range. This causes the tip of the vector whose x and y coordinates are the in-phase and quadrature voltages to trace out an ellipse. The center of this ellipse defines the zero offset errors (δ_c and δ_s) and the major and minor axis define the relative gains of the two detector channels (α_c and α_s). During the remainder of the internal calibration period, the strength of the calibration signal is changed to provide the variations of the channel amplitudes and phases (A and ϕ) with AGC level. The final step is to establish the absolute values of the channel amplitude and phase factors at a reference AGC level. This is done by comparing the measured values to stored reference values. These reference values are obtained by performing an internal calibration in conjunction with a complete external calibration such as described in the previous section. The reference values are determined in the computer and are those which would have been measured if the system was perfectly aligned. That is, they are the values measured when the internal calibration signal is not corrected for the channel amplitude and gain errors determined from the external calibration signals.

SECTION VII
ANTENNA SUBSYSTEM

7.1 ANTENNA SELECTION CRITERIA

7.1.1 POWER BUDGET CONSIDERATIONS

In order to design the antenna system it is necessary to estimate the available power budget which in turn will define the required antenna gain.

We will assume that the aircraft is ten miles away and radiates 100 watts (typical radiated power is 300 watts). We will stipulate the aircraft antenna gain is 0 dB and will allow a 10 dB fade margin. The transmission loss of a 1 GHz signal at 10 miles is 117 dB. The available signal can be estimated as follows:

Radiated Power	+50 dBm
Aircraft Antenna Gain	0 dB
Fade Margin	-10 dB
Transmission Loss	-117 dB
Available Signal Level	-77 dBm

To accommodate .45 microsecond pulses it will be necessary to have a receiver bandwidth of 5 MHz. Theoretical noise figure (KTB) is -107 dBm. Assuming 8 dB noise figure and specifying signal-to-noise ratio of 40 dB the desired signal level is:

Theoretical KTB Noise Level	-107
Receiver Noise Figure	8
Signal-to-Noise Ratio	40
Desired Signal Level	-59

The 18 dB discrepancy between the desired and the available signal levels must be made up by the antenna gain.

The above estimate of aircraft radiated power, depth of fades and receiver noise figure has purposely been made pessimistic in order to insure that a very adequate signal-to-noise ratio will always be available.

7.1.2 ELECTRICAL REQUIREMENTS

The antenna subsystem must meet a number of significant electrical requirements. The most important of these are discussed in this section.

In order to operate with the aircraft transponder signal the polarization must be vertical and the performance must be optimized in the frequency range between 1.0 and 1.1 GHz.

The element designs described in Section 7.2 are based upon design criteria of 18 dB gain and 20 degrees vertical and horizontal beamwidth. These criteria are arrived at in the following manner.

The element gain must be of the order of 18 dB in order to achieve the required signal-to-noise ratio (see Section 7.1.1 for the power budget computations). The vertical patterns of the elements must be centered near the horizon and their shapes matched to within 0.1 dB within the elevation angle range of ± 5 degrees. Experience has shown that such a match can be maintained reliably only if the beamwidth is at least twice the match range. Thus, a minimum vertical beamwidth of the order of 20 degrees is required. The horizontal beamwidth is constrained in part by the gain and vertical beamwidth. Assuming a typical aperture efficiency, the product of the vertical and horizontal beamwidths must be of the order of 400(degrees squared) in order to achieve a gain of 18 dB. Consequently, the horizontal beamwidth must be 20 degrees or less.

The number of antenna elements and the element spacings are determined by the angular accuracy requirements imposed on the WASS system as well as physical constraints imposed by the fact that the system must operate in an airport environment. These requirements lead to the vertical antenna configuration shown in Figure 7-1 which employs five antennas arranged to give three sets of three antennas with element spacings of 5, 7.5, and 10 feet respectively. These numbers are arrived at as follows.

The accuracy requirements are comparable to those achieved in tests of the WASS system using a total aperture of 100 inches at S-band (refer to Section 3.5). Simple frequency scaling leads to an overall aperture of about 23 feet. This is met by an element spacing of 10 feet. With this spacing however, the ambiguity interval is approximately 5 degrees which is unacceptable for this application since targets above 2.5 degrees will be ambiguous and will appear to the system to be at a negative angle. In order to eliminate this ambiguity an antenna set with a shorter spacing is required. The fourth antenna introduces a set with a spacing of 2.5 feet. With this spacing the ambiguity interval is 20.8 degrees which means that targets within the elevation angle interval ± 10.4 degrees are unambiguous.

The height of the bottom antenna is constrained in two ways. First, the minimum height should be high enough so that people

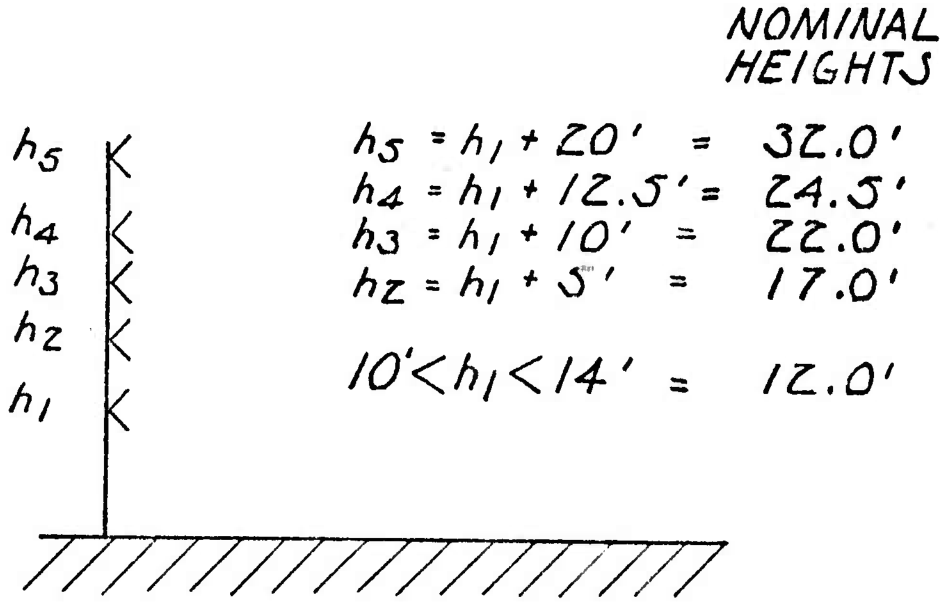

FIGURE 7-1 ANTENNA CONFIGURATION

and/or vehicles cannot position themselves directly so as to block the antenna aperture. A minimum height of ten feet should satisfy this constraint. Secondly, the performance of the WASS system degrades considerably if the relative phase of the direct and reflected signals, as seen at the center antenna of the triad is within 30 degrees of either zero or 180 degrees. This relative phase for an antenna at height h_i is Δ_i where

$$\Delta_i = (4\pi h_i/\lambda)\sin\alpha+\theta_0$$

where θ_0 is the phase of the reflection coefficient. The phase at the i'th antenna is a linear function of the phase at any other antenna. In particular

$$\Delta_i = (h_i/h_j)\Delta_j-\theta_0[(h_i/h_j)-1].$$

This relationship is plotted in Figure 7-2 for h_i-h_j = 2.5, 5, and 7.5 feet and values of h_i = 15 and 19 feet. The reflection phase is assumed to be -180 degrees. The lines terminate at an elevation angle of 5 degrees. The shaded squares show the regions where both Δ_i and Δ_j are within 30 degrees of either 0 or 180 degrees. From an examination of this type of plot it is clear that there exists no spacing which can avoid the simultaneous degradation of the performance of two WASS triads. Three triads can be selected however so that the performance using at least one of them is not degraded. One choice which accomplishes this is to have a 5 foot spacing between the centers of the lower two triads and a spacing of 7.5 feet between the centers of the top and bottom triads. Subject to this condition, the height of the center of the bottom triad above the ground may be anywhere between 15 and 19 feet which places the bottom antenna between 10 and 14 feet and the top antenna between 30 and 34 feet. Thus, we are led to the antenna configuration shown in Figure 7-1 with antenna element centers nominally located at 12, 17, 22, 24.5 and 32 feet above the ground. The minimum antenna spacing of 2.5 feet means that the vertical aperture of the antenna elements must be less than this size. The vertical element beamwidth will therefore be greater than 20 degrees as required.

This completes the discussion of the electrical specifications as they define the WASS sampling array and the sampling elements themselves. Two alternative sampling elements satisfying these requirements are described in Section 7.2.

7.2 WASS SAMPLING ANTENNAS

7.2.1 ELECTRICAL DESIGN

The electrical criteria limiting this design have been discussed previously. The vertical aperture is limited to approximately 2.5 feet by array spacing requirements. The gain requirements then dictate a horizontal aperture of the order of 3 feet or more. Three fundamental antenna types present themselves. These are horns, reflector antennas, and Yagi antennas.

The Yagi antenna itself is mechanically the simplest antenna type. To achieve the gain of 18 dB would require a total length of about 4.5 feet and 15 elements. The physical problem of mounting an array of vertically polarized Yagi's is the primary problem area. There are some uncertainties concerning the coupling between the two elements spaced 2.5 feet apart if Yagi antennas are used. Relatively high sidelobe levels and a relatively low front to back ratio are other problem areas.

The horn antenna has inherently low coupling and a good front to back ratio. For a 2.5 foot E-plane dimension and a 3 foot H-plane dimension with a gain of 18 dB the horn length (exclusive of the feed waveguide) must be of the order of 3 feet and the vertical and horizontal beamwidths will be of the order of 30 and 16 degrees respectively.

There are several types of reflector antennas which could be used. The standard parabolic reflector does not appear to be a good choice for mechanical reasons. A solid reflector would present too much wind loading and forming the two dimensional reflecting surface from wire mesh would probably be unnecessarily expensive. A simple dishpan reflector is possible but, since the aperture illumination is not very efficient, would have to be larger in order to meet the gain requirements. In addition, feed spillover and element cross coupling present additional problem areas. A parabolic cylinder with a line feed represents an attractive approach. In order to minimize coupling, fences between the elements would probably be required leading to an antenna element such that shown in Figure 7-3. This antenna would have a depth of 2.25 feet which is certainly acceptable. The one dimensional curvature lends itself well to wire mesh construction and the line feed can be easily implemented. The method of exciting the line feed from the center that is shown in the figure is only one of several possible feed excitation methods.

The most attractive antenna element is the parabolic cylinder.

7.2.2 MECHANICAL DESIGN

The principle mechanical features to be considered are wind

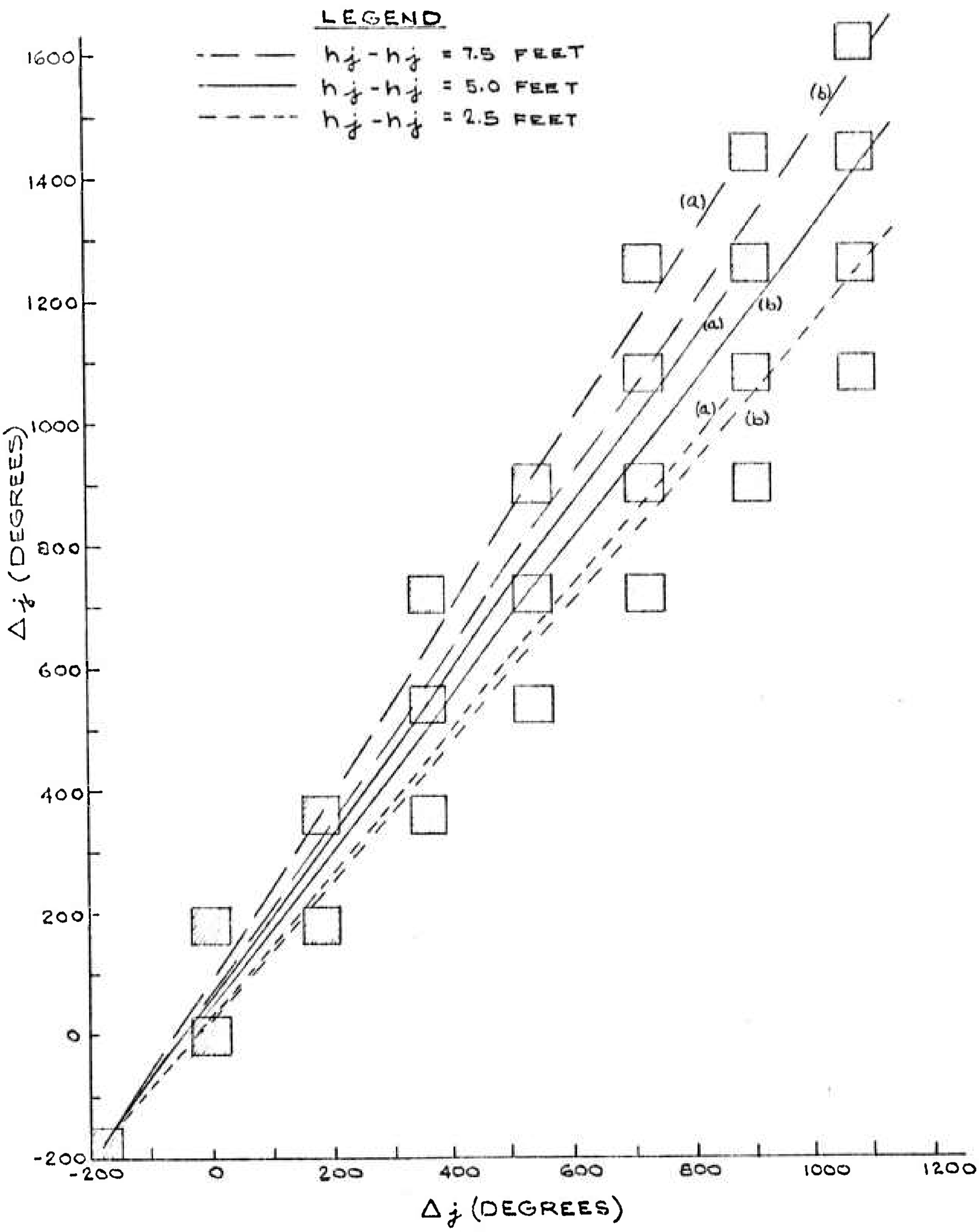

FIGURE 7-2

RELATIVE PHASE OF DIRECT AND REFLECTED SIGNALS AT TWO SAMPLING ANTENNAS.
a) h_j = 15 FEET, b) h_j = 19 FEET.

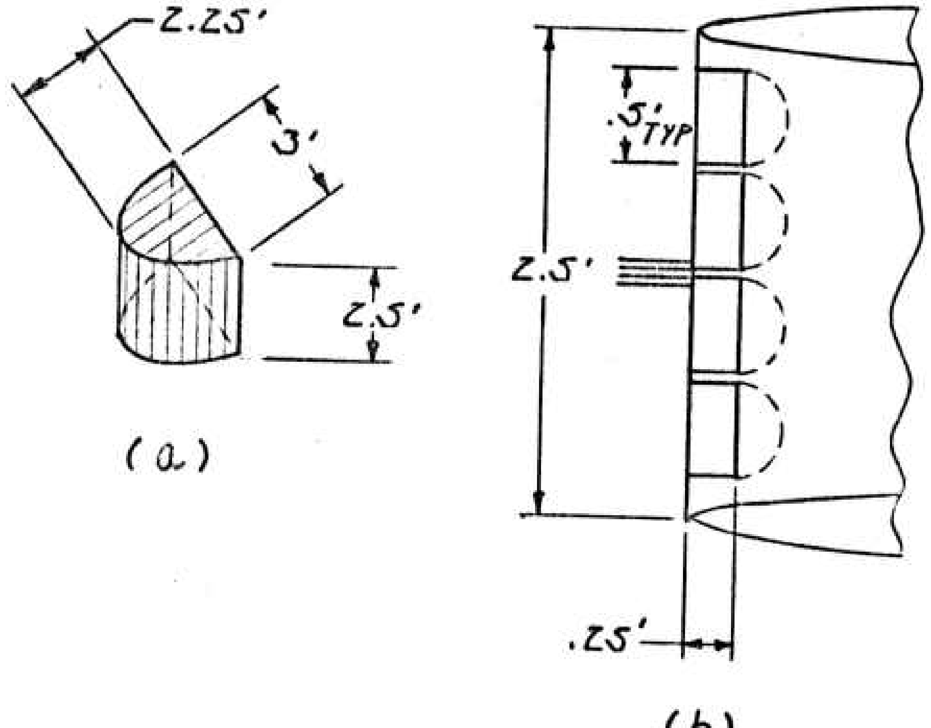

FIGURE 7-3 PARABOLIC CYLINDER ANTENNA
(a) REFLECTOR
(b) LINE FEED

loading and support structure complexity. The wind loading is important since it is desirable that the baseline orientation be relatively free of motion at all times. Obviously, the more the wind loading, the greater the amount of support structure rigidity required to insure a given maximum deflection. Wire mesh (0.50 inch mesh) construction of the "solid" surfaces of horn and reflector antenna types will minimize the wind loading effects for these antennas without degrading the electrical requirements of a "solid" surface.

The physical construction of a Yagi antenna element is standard and consists essentially of joining lengths of tubing to a central boom. The parabolic cylinder antenna would be constructed of wire mesh stretched over a framework of aluminum tubing.

The mechanical support of an array of vertically polarized Yagi antennas which are more than four feet long is a difficult problem. The entire active length of the antenna must be in front of any vertical support structure which would require a thick central boom in order to avoid drooping. This factor combined with probable complications from mutual coupling pretty well eliminated the Yagi antenna from serious consideration in this application.

The vertical array of parabolic cylinders can be supported by three vertical poles as shown in Figure 7-4. The vertical poles form a triangular tower with the cross bracing consisting of the framework of the parabolic cylinder antennas. This structure is inherently stable and can be further stabilized by guy wires.

7.3 FULL MONOPULSE COMPATIBILITY

In an operational system the WASS landing monitor will handle both the elevation and the azimuthal angles of arrival. The elevation angle information will be derived in the normal monopulse mode when the aircraft is well above the ground and will be switched to the wavefront sampling mode when it is determined that the wavefront departure from the plane wave exceeds preprogrammed threshold. The azimuthal information will be derived by using two identical vertical arrays side by side. Signals from each of the elements will be combined and appropriately phased and processed by the computer to provide normal monopulse capability in both azimuth and elevation. If necessary, the problem of 20° ambiguity resulting from placing the antennas side by side will be resolved with the standard technique using an auxiliary antenna.

It should be emphasized, of course, that since the azimuthal

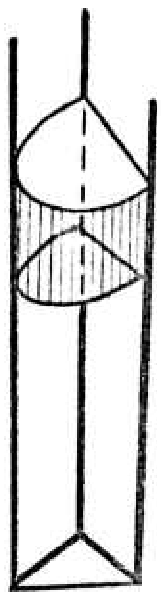

FIGURE 7-4 SUPPORT STRUCTURE FOR PARABOLIC CYLINDER ARRAY.

monopulse capability is currently achievable with standard techniques, the emphasis of the present effort has been directed mainly to the resolution of the vertical angle.

Extension of the WASS landing monitor to provide azimuthal monopulse will be straightforward. It will require duplication of a vertical array and additional receivers. The software complications are very minor, since suitable programs have been developed to handle this situation under previous RADC efforts and are described in the RADC Technical Report TR-71-262.

SECTION VIII

INTERROGATION AND RANGING

8.1 GENERAL CONSIDERATION

The objective of the interrogation subsystem is to elicit responses from all ATCRBS transponders in a selected interrogation volume. This will be accomplished using pulsed interrogation signals in conformance with Federal Aviation Administration Order No. 1010.51, U. S. National Standard for the IFF Mark X Air Traffic Control Radar Beacon System Characteristics. The ATCRBS airborne transponders will thereby transmit pulses on the response frequency in exactly the same manner as for their normal usage.

The design objective on the interrogation subsystems is to make use of directive antenna patterns to confine the radiated energy along a beam in both azimuth and elevation angles which encompasses the volume of air space required for overall system functioning, but no more than the amount required. By reducing the power level of the transmitted interrogations, the range along the antenna beam for which the power level is adequate for triggering airborne transponders may be reduced considerably below that which is normally used for the Airport Surveillance (ASR) function. By limiting both range and angle we can minimize the interference which this system produces for other functions for which the ATCRBS may be utilized such as airport surveillance radar operations.

The response pulses from the airborne transponders are utilized via the WASS system to measure angles and measure range, thus pinpointing the airborne interrogator as described elsewhere in this report. There are two alternative methods of obtaining necessary range data. The first is the direct method of measurement of time delay between the interrogation pulses and the received response pulses, which technique suffers from a small uncertainty in the measured range in that the time delay in the transponder is not precisely controlled. The second alternative for range measurements proceeds by measuring angles of arrival at two separate antenna locations thus enabling the computer to establish position of transponder by triangulation computations.

8.2 RESPONSE VOLUME

The response volume defining the zone from which responses are obtained is primarily a function of the beamwidth pattern of the interrogation antenna. In the azimuth plane it is desired to limit the zone to a total width of 20°, in range we desire cover-

age out to 10 miles. Using a simple directive antenna does not produce this coverage zone because at closer ranges signal levels on the sidelobes or skirts of the antenna beams will be adequate for transponder operation thus producing responses from aircraft outside the 20° zone. For those transponders equipped with sidelobe suppression (SLS), use may be made of this feature to eliminate responses which might otherwise occur on the skirts or sidelobe of the antenna beam pattern. Figure 8-1 illustrates how this functions. The interrogation pulse consists in part of the first pulse called P1 transmitted on a directional antenna followed by a second pulse called P2 transmitted on a omnidirectional antenna, and the design criterion of the transponder requires that the P1 pulse be at least 9 dB above the P2 pulse for proper transponder action. Thus, by utilizing a directive antenna having a main lobe width of 20° at the 6 dB down points, and by utilizing an omnidirectional pattern so excited that its power level for the P2 pulse is 9 dB below the pattern width of the directional antenna, transponder action will only be obtained within the 6 dB points of the directional antenna pattern.

In the vertical plane, the antenna pattern is influenced by surface reflections which may induce a lobing structure in the directive antenna pattern. For the sidelobe suppression technique to function properly the lobing structure of the omnidirectional antenna should be nearly identical of that obtained from the directional antenna. This can be assured by utilizing a vertical omnidirectional antenna whose phase center is at the same height above ground as the directional antenna and whose aperture in the vertical plane approximates the aperture of the directional antenna.

The WASS receiving antennas may be utilized for interrogator transmission in order to minimize the expense of additional antenna structures. By using three of these antennas we may form a simple phased array to achieve the beam shaping desired. The omnidirectional antenna may be realized most simply by a series of dipole radiators, one above the other, each at the height of the corresponding horn antenna of the WASS array. The omni is displaced from the WASS array so that the two antenna structures do not interfere with each other. The phasing and the excitation levels of each of the dipoles may be adjusted to be identical to that used in the interrogator directive antenna array, thus assuring identity in the vertical pattern in the two antennas. Thus, valid sidelobe suppression operation is obtained at all vertical angles in the desired response volume.

Table 8.1 is a power budget for the transponder interrogation up link. Transponder sensitivity varies from -69 dBm for the

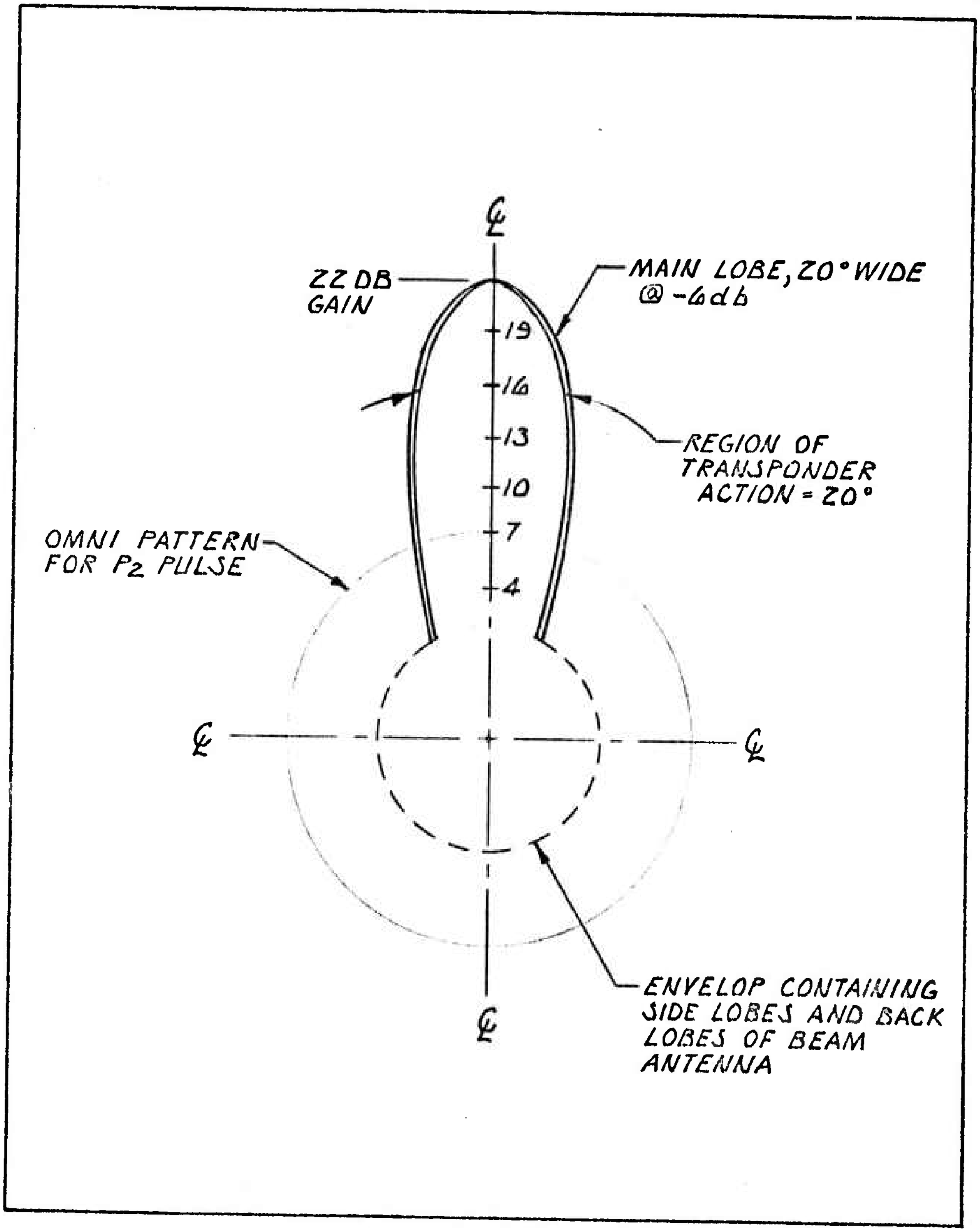

FIGURE 8-1 SIDE LOBE SUPPRESSION FEATURE OF ATCRBS MAINTAINS AZIMUTHAL COVERAGE AT 20°.

TABLE 8.1
TRANSPONDER INTERROGATION POWER BUDGET

	LEAST SENSITIVE TRANSPONDER	MOST SENSITIVE TRANSPONDER
Transponder Sensitivity	-69	-77 dBm
Assumed Line Loss, Aircraft	-3	-3 dB
Assumed Aircraft Antenna Gain	+2	+2 dB
Equivalent Isotropic Transponder Sensitivity	-68	-76 dBm
Interrogator Antenna Gain	+22 dB	+22 dB
Interrogator Line & Diplexer & Switch Loss	-3	-3 dB
Interrogator Effective Antenna Gain	+19 dB	+19 dB
Path Loss (37+20 log f_{MHz} D_{mi})	118 dB	118 dB
Transmission Loss from Interrogating Antenna Terminal	99 dB	99 dB
Transmission Power (Transponder Sensitivity + Equivalent Loss)	31	23 dBm
Allowance for Field Degradation	6	6 dB
Required Transmission Power	37	29 dBm
Required Transmission Power	5 watts	0.8 watts

least sensitive transponder to -77 dBm for the most sensitive transponder. Utilizing typical aircraft line loss and antenna gain figures the equivalent isotropic transponder sensitivities are calculated as shown in the table. Interrogator antenna gain is estimated at +22 dB. Allowing for line, diplexer, and other losses of 3 dB results in an effective interrogator antenna gain of +19 decibels. At a frequency of 1030 MHz and a distance of 11 miles (corresponding to the range from the WASS antenna site to the aircraft at the outer limit of the desired volume of interrogation) produces a path loss of 118 dB. Subtracting the effective antenna gain from this figure produces a net transmission loss of 99 dB. Adding this loss to the transponder sensitivities yields the required transmitter power. To these numbers we have added 6 dB allowance for field degradation (i.e., a design margin). The net result is for the least sensitive transponder a 5 watt power level is required whereas for the most sensitive transponder a required power level is 0.8 watts. The design, of course, is based on the 5 watt level which implies that if there is no system degradation, and a transponder of maximum sensitivity is involved, the range is not limited to the 11 mile figure used in the table. The additional range amounts to a power ratio of 14 dB corresponding to a 5:1 ratio in ranges so that the maximum range becomes 55 miles. Figure 8-2 is a plan view of the area surrounding a landing field. A 200 mile range is shown as a typical range for normal ATCRBS operation (providing aircraft altitude is sufficient) where directive antennas, together with high power levels, are continuously scanned in azimuth to cover the entire volume. The region of space in which beacon transponder action is initiated by the WASS system is plotted in the figure and it is evident that a relatively few number of aircraft will be spuriously triggered. Thus interference is minimized even at high pulse repetition frequencies for the WASS interrogations.

8.3 ANTENNA AND RF COMPONENTS

Figure 8-3 is a block diagram of the general scheme for the interrogation transmissions. Three antennas of the WASS vertical array of antennas are utilized as a phased array excited by three power amplifiers providing controlled phase and excitation levels at each of the antenna terminals. For example, the upper and lower antennas may be excited with 1 watt of power and the center antenna excited with 4 watts to achieve a total of 6 watts of radiated power into the array. The antennas are connected by means of PIN diode switches. For the P2 pulse which is to be transmitted via the omnidirectional antenna a PIN diode switch connects an LO power splitter port to a power amplifier connected to the omnidirectional antenna. These PIN diodes also serve as pulse modulators, i.e., they may be operated in a controlled fashion to

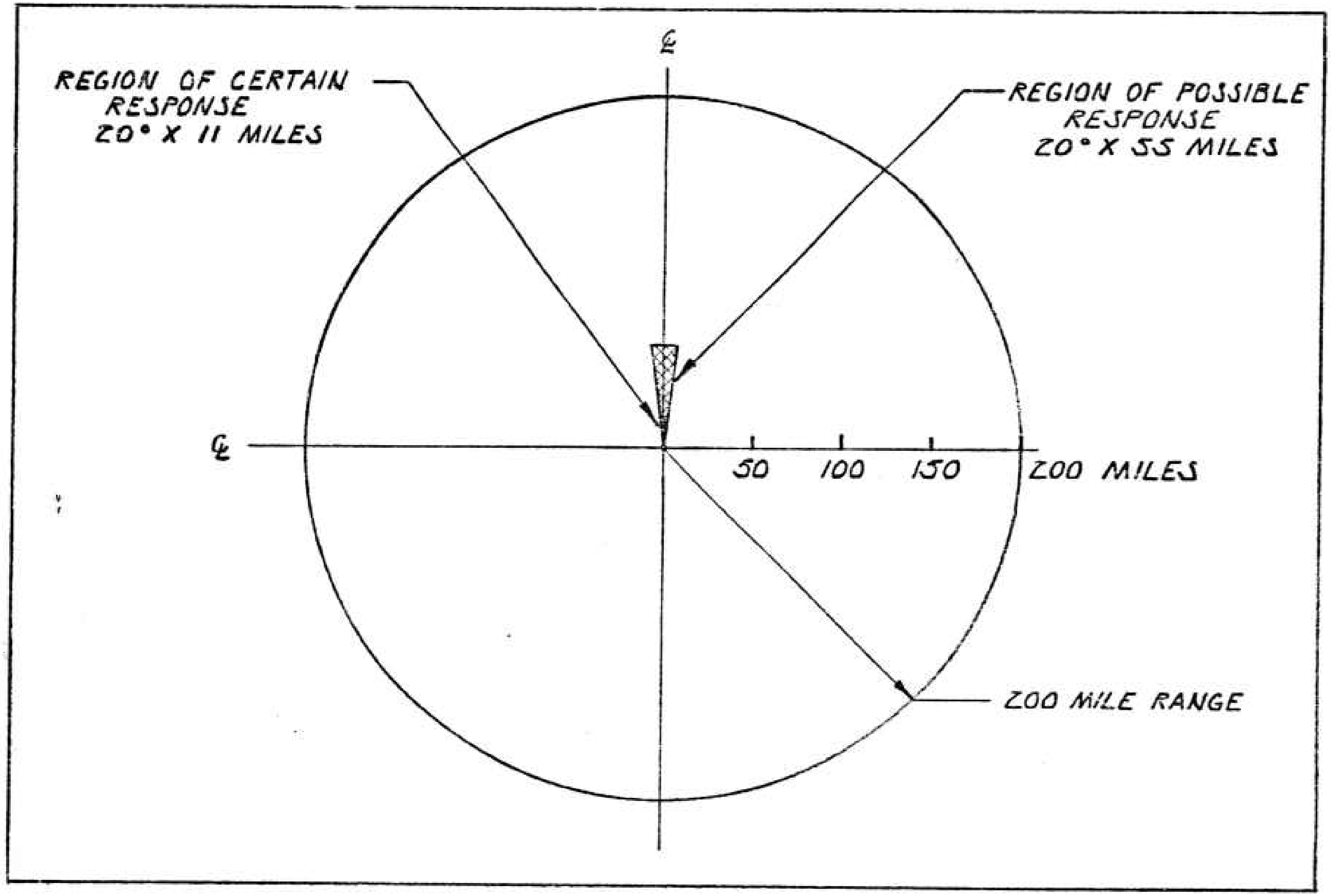

FIGURE 8-2 ATCRBS RESPONSE AREA - MINIMIZED FOR MINIMUM INTERFERENCE WITH OTHER ATCRBS USERS.

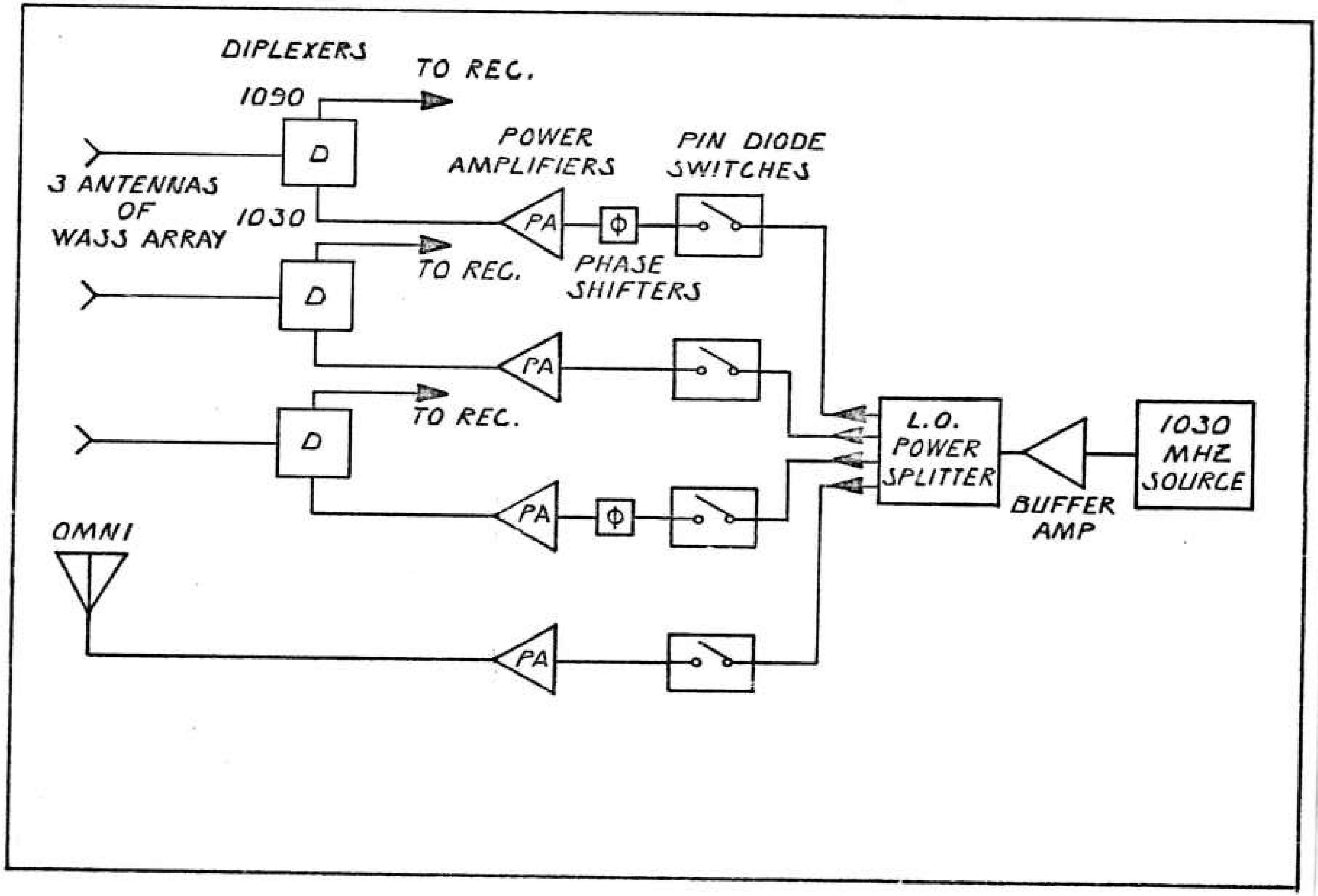

FIGURE 6-3 INTERROGATION TRANSMISSION

achieve the required pulse widths and pulse rise times necessary for proper system operation in accordance with accepted standards.

Alternatively of course a separate interrogator directional antenna aperture could be utilized. However, to achieve the desired goal of triggering transponders only in the controlled volume a rather large structure would be implied so that utilization of the WASS receiving antennas for this purpose minimizes the expense in construction and installation of antennas at the cost of relatively inexpensive PIN diode switches and the logic circuits necessary to drive them.

Figure 8-4 illustrates the vertical geometry involved in the landing approach pattern and WASS antenna siting. This figure shows a horizontal scale from 0 to 10 miles representing distances along the ground, and a vertical height scale from 0 to 3,000 feet. The origin of the axes is the ground path intercept point (GPT). This point is an extension of the glide slope as it intersects the surface. Approximately 1 mile behind this point will be located the WASS antenna site. Glide slope path angles between 1 and 4° are of most interest, shown as lines OA and OC in the figure. Entry into the controlled zone is generally between altitudes of 1,000 and 2,500 feet. Thus, an area bounded by the points OABCO in the diagram contain the points of most interest to the systems designer. Note that this volume implies vertical angles as seen by the WASS antenna site between .93 and 3.48° above horizontal. Of course, coverage somewhat outside this zone is also required for aircraft initially off the required flight path.

After a considerable computer study using realistic values for ground reflection, it was concluded that the utilization of antennas Nos. 1, 2, and 3 in the WASS array (see Figure 7-1) for aircraft interrogation will provide satisfactory coverage.

Figure 8-5 shows the computed vertical lobing structure for an interrogator antenna utilizing the 3 WASS antennas at heights of 17, 22, and 24.5 feet with equal power applied to each at 1030 MHz. Ground constants were dielectric constant of 2.5, conductivity 0.003 corresponding to asphalt or dirt material. This computation takes into account the complex reflection coefficient antenna element pattern and the path difference to determine a composite radiation pattern. Phasing between elements is adjusted (for this particular computation) to aim the free-space beam upward at an elevation of 3.0 degrees. Data is presented as contours of constant field intensity over the vertical area of prime interest, i.e., out to 10 miles and up to 2,500 feet altitude, in the area bounded by the polygon OABCO in the figure. Note that

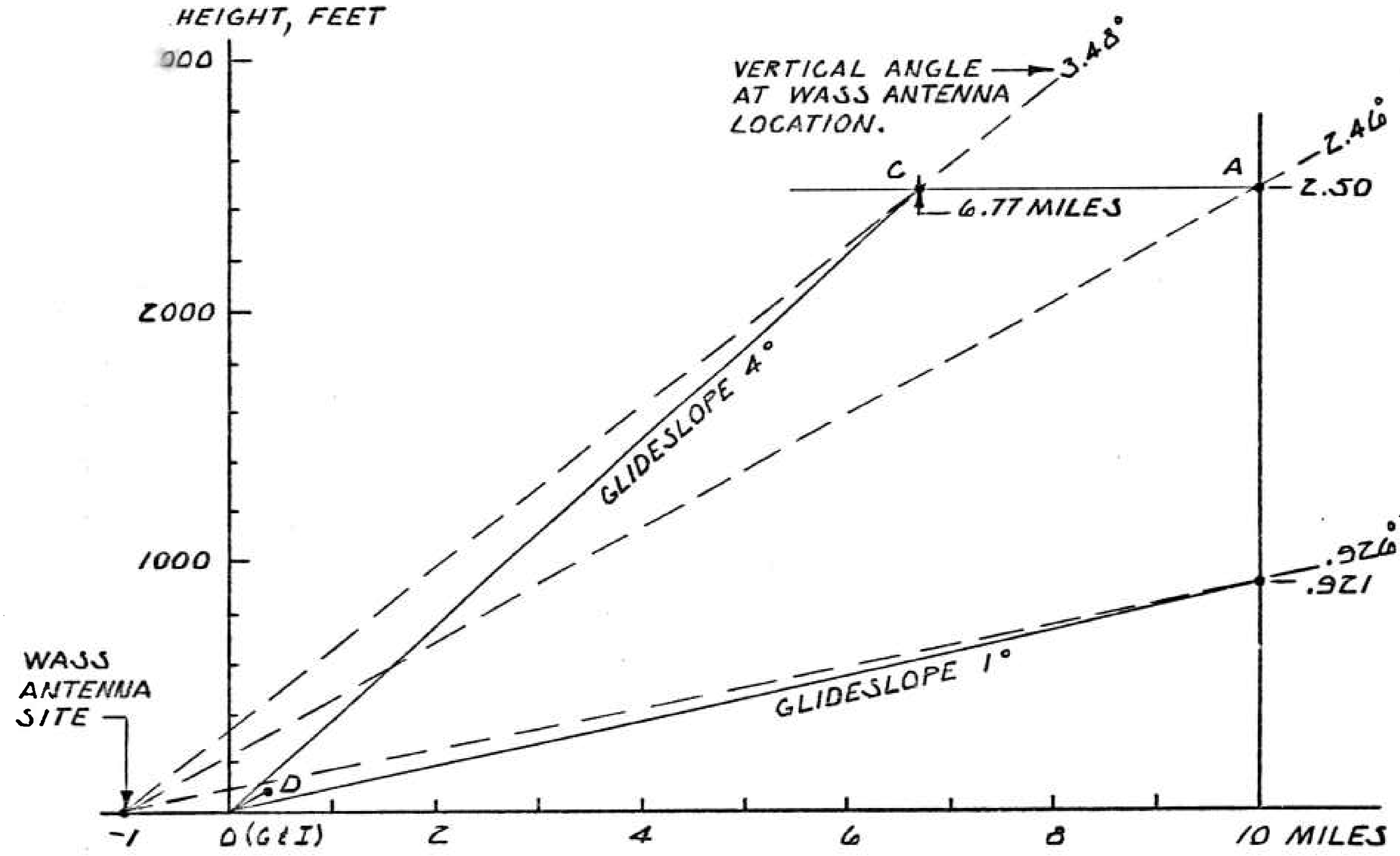

FIGURE 8-4 GLIDESLOPE GEOMETRY

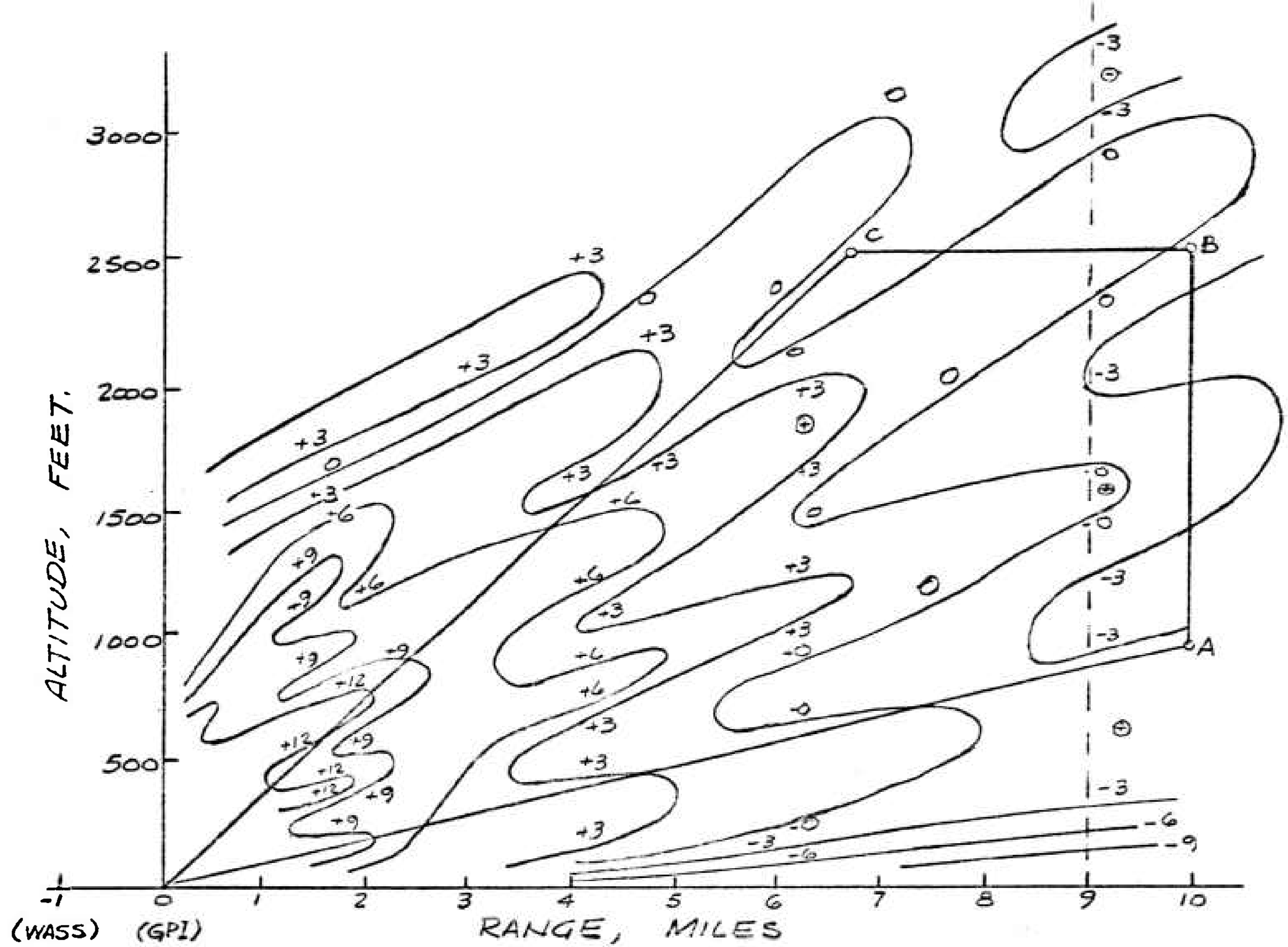

FIGURE 8-5.
INTERROGATION SIGNAL INTENSITY CONTOURS

while there is some lobing (signal variation) in the area of interest, the degradation amounts to only -3 dB. Thus deep nulls have been avoided, and reliable transponder operation is assured in the critical region, and for considerable deviation outside the polygon OABCO. Since the reflection point (Fresnel region) is near the WASS antenna site, it will be in an area on or near the runway, a region that may be expected to be relatively flat and smooth. Thus we expect close agreement between calculated and actual results. Furthermore, while the details of the lobing structure may change with ground conductivity and dielectric constant, the essential feature of small signal degradation in the critical area will pertain to all ground conditions. Thus, a design based on fixed parameters (antenna heights, phasing, and relative excitation of each antenna) will achieve the desired result: reliable transponder triggering throughout the zone of interest.

Some of the interrogation circuit elements depicted in Figure 8-3 have been subjected to breadboard design and construction. Figure 8-6 illustrates a 1.09 GHz RF power amplifier. The circuit is constructed in microstrip form using conventional RF circuit board material. Primary elements of cost are the power transistor itself and a single tuning capacitor for matching input impedance. Other circuit elements consist of inexpensive capacitors and coils. The circuit operates at 50 ohm input and output impedance levels and achieves a gain in excess of 10 dB. Figure 8-7 shows a single pole double throw PIN diode switch which may be used as a pulse modulator. The diodes are the small black rectangular elements between the large tuning screws and the 50 ohm line which is visible between the ground planes. Since operation is over a narrow bandwidth, it is possible to tune the diodes capacitance for the diodes in the OFF state so that a large package capacitance can be tolerated. Likewise in the diode ON state (switch OFF) the diode series inductance is resonated with a series capacitor. The end result gives response over a narrow bandwidth which is nevertheless entirely adequate for the application at hand, yet permits realization of the circuit with inexpensive PIN diodes. The diodes shown in the photograph were purchased in small quantities at less than $1 a piece. This circuit functioned both for switching and pulse modulation, providing approximately 0.5 dB attenuation in the ON state and in excess of 30 dB rejection in the OFF state. If additional isolation is required of course additional diodes may be utilized.

8.4 DETERMINATION OF RANGE

In order to determine all three Cartesian coordinates of the aircraft, the slant range will be measured, along with the two

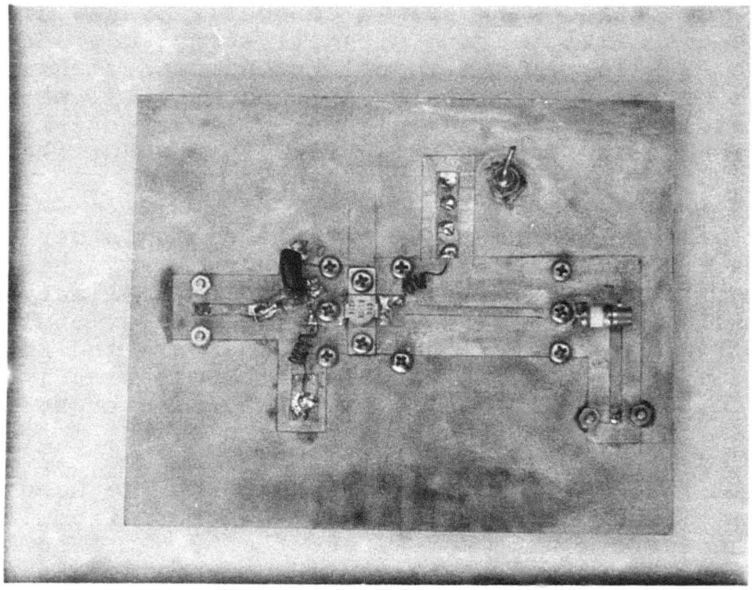

Figure 8-6

Breadboard of 1.09 GHz Interrogation Signal RF Power Amplifier

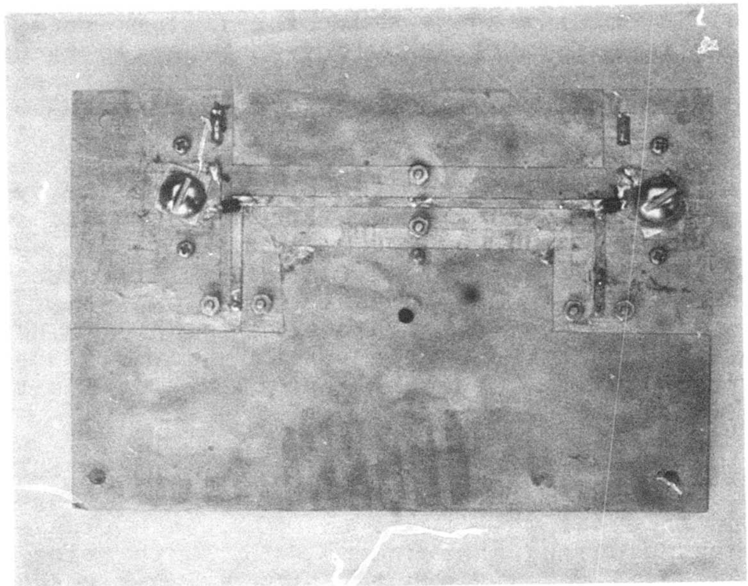

Figure 8-7

Breadboard of PIN Diode Switch

angles of arrival of the radiation from aircraft to WASS site. The ATCRBS transponders are required to provide a transponder delay within ±0.5 microseconds of the nominal value of 3.0 microseconds. This wide tolerance implies an uncertainty of round trip propagation time of a like amount, and represents a bias in the delay which no amount of data smoothing will alleviate. Thus, if slant range is measured by a time delay measurement, the uncertainty will be ±250 feet, which value will mask other sources of error such as transponder jitter, and receiver noise, both of which may be easily minimized by smoothing filter processing routines within the computer. It should also be noted that the state of the electronic art has surpassed such loose tolerances, and future transponders (such as those contemplated for DABS) could easily employ tolerances of 100 nanoseconds or less.

The principal effect of a 250 foot error to the system under discussion would be to cause the aircraft to be guided along a glide slope that is in error by 250 feet, measured along the runway. Thus, the aircraft could land (assuming zero-zero visibility) 250 feet short of or beyond the planned touchdown point. On a 10,000 foot runway, this effect would seem to be of minor consequences, and is accommodated by the system under discussion by placing the origin (Glide Path Intercept Point) at least 250 feet within the runway.

Aside from the construction of (future) transponders with a closer tolerance on their turnaround time, greater range accuracy may be obtained in other ways. For example, each transponder could be calibrated during maintenance, the calibration recorded on the ATCRBS control panel, and used as a "squawk code" for pilot manual response prior to entering the final approach area. The information could also, of course, be transmitted by voice over radio communication facilities. These methods, while technically feasible, are undesirable in that they add one more task for the overburdened pilot making an instrument landing.

Another way of determining range with more accuracy is by means of triangulation. This would involve a second monopulse antenna which measures horizontal angle of arrival at opposite ends of a baseline. The triangulation computations would be handled by the computer, and range measurements as such would not be necessary. This approach has the feature that the accuracy of range computation increases as the aircraft approaches the baseline. It has the disadvantage of requiring more antennas and equipment.

It is concluded that the best approach is simply to tolerate the ±250 foot error in the manner indicated, since it is accommodated by a simple choice in system geometry. A maintenance disci-

pline for transponders, in which the tolerance of delay is checked out for compliance to the 3.0 ±0.5 microsecond requirement, is advisable in any event.

Range measurement by time delay is easily accomplished by present day digital circuits. A simple scheme for achieving it is shown in Figure 8-8. A crystal controlled oscillator provides a precision time interval corresponding to the least significant bit of the measurement. At the time of transmission of an interrogation pulse, a high speed binary digital counter is reset to zero, and counts upward until a response pulse is received from the aircraft. The leading edge of the first pulse in the aircraft response activates a pulse generator which gates the counter value into the computer, thus giving the computer a digital version of the time delay between interrogation and response pulses. After the first pulse of the response is received, the high speed counter continues to operate, with subsequent pulses in the response being ignored until a period corresponding to the maximum message length from the transponder has elapsed. After this time interval, subsequent response pulses are accepted as those from potential "other" aircraft, and transferred to the computer. By using a direct memory access input port of the computer, the computer operation is not interrupted as the various range delays are inputted into the computer.

The search and track algorithms contained in the computer program provide for checking consistency of data to establish a "track", and for smoothing the data corresponding to each track so established. Occasional hits from noise or non-interrogated aircraft responses will, in general, not be consistent with the counter reset time, so are rejected by the computer. Thus, multiple target tracking with optimum data smoothing becomes a matter of computer software, and capability in this regard can grow as the system grows, without requiring hardware changes.

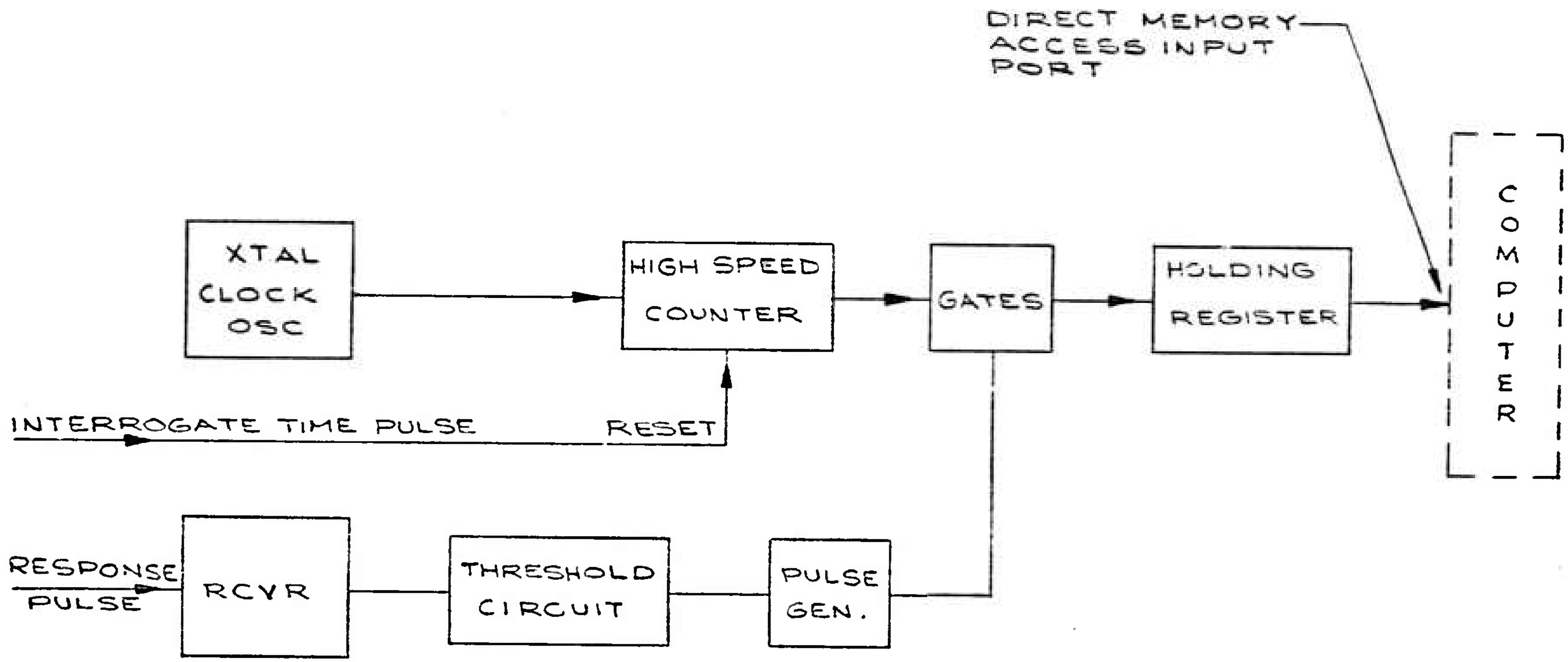

FIGURE 8-8

RANGE MEASUREMENT

SECTION IX
WASS RECEIVING SYSTEM

The WASS receiving system described here is a five channel coherent system utilizing carefully matched IF preamplifiers and amplifiers to accomplish the accurate measurement of the relative amplitudes and phases of the voltages appearing at the five antennas of the WASS array. Since only three antennas are used at a time to provide the separation of two components, three receiver channels could have been utilized with RF switching between the antenna outputs and the channel inputs. In the interests of reliability and performance it was determined that the use of five channels would provide a better overall system. Loss of any one channel in the system would reduce the number of combinations of array elements possible but would not cause the entire system to become inoperative. Also, the use of three antennas simultaneously to derive the correlation reference signal results in considerably better performance than the use of a single antenna because of the resultant array pattern.

The receiver is broken down into two main parts. The RF head, which is located at the antenna, and the receiver main frame which is remotely located inside the building. The receiver is essentially a fixed tuned system with only sufficient tuning provided in the form of automatic frequency control to track the relatively unstable transmitters in the aircraft. The receiving system is described in detail in the following sections.

9.1 SYSTEM BLOCK DIAGRAM

Figure 9-1 is a simplified system block diagram of the WASS receiving system. The RF head contains the five matched mixer-preamplifiers, the associated local oscillator, and the calibration reference oscillator for injection of a signal of fixed relative amplitude and phase into the inputs of the five RF channels. The RF head is mounted on the antenna structure in the weatherproof enclosure and the RF lines from the antennas to the RF head are of equal length to minimize differential path length changes due to heating and cooling effects. The IF outputs from the mixer preamplifiers are carried through five coaxial cables to the mainframe located within the building. Power and control signals to the RF head are derived from the receiver mainframe and applied to the RF head through a multiconductor cable.

The receiver mainframe contains the five matched IF amplifier channels, the AGC detector circuitry, and five identical cross correlators with dual sample-and-holds to provide quadrature components of amplitude as outputs from the system. The mainframe

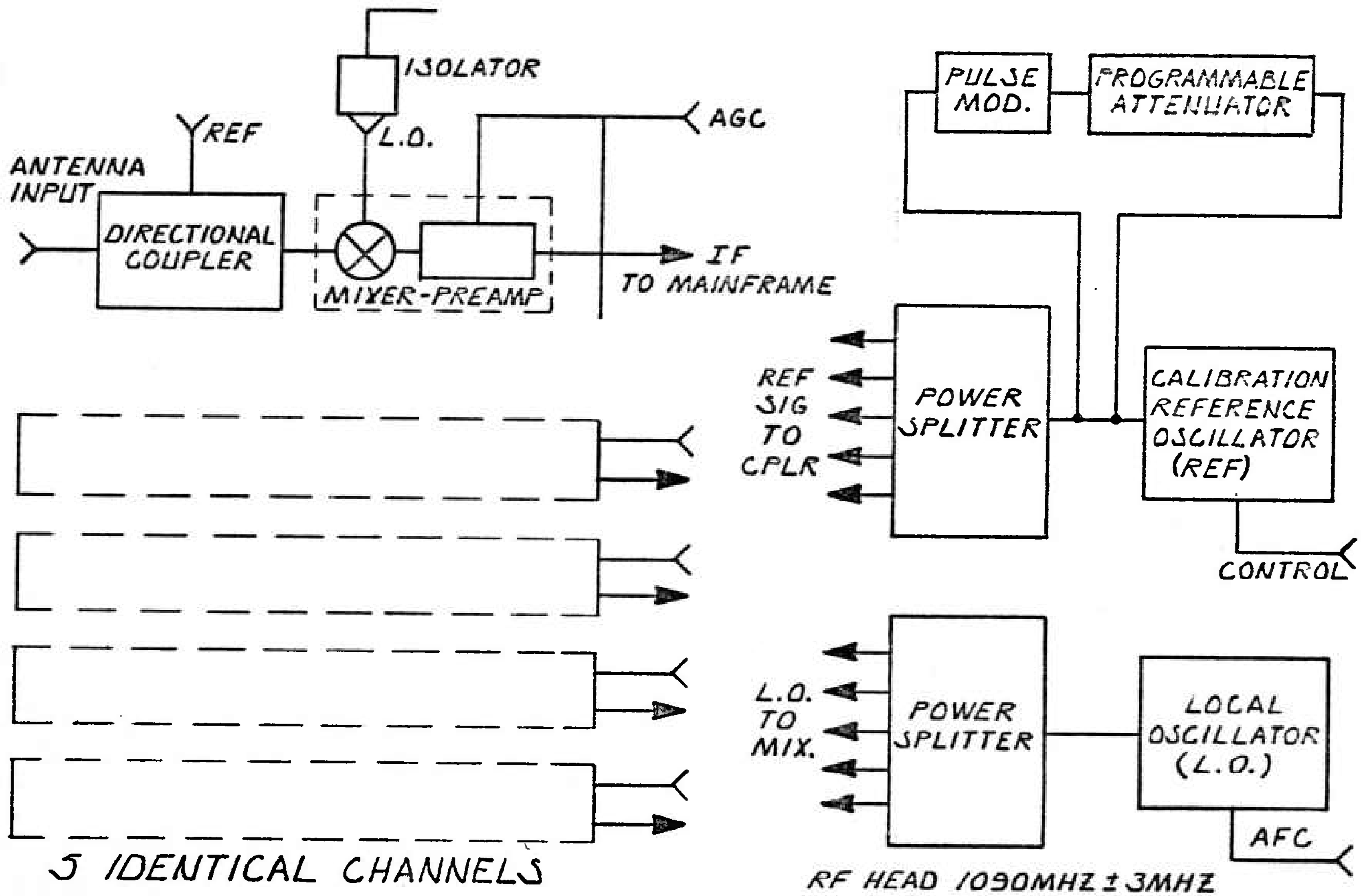

FIGURE 9-1 SIMPLIFIED BLOCK DIAGRAM OF THE WASS RECEIVING SYSTEM.

also contains the necessary circuitry for developing the reference inputs to the cross correlators for detection of the video pulse for monitoring purposes and for developing automatic frequency control voltage to the local oscillator. Because of the large number of modules in the receiver mainframe, the power supplies for the receiving system are located in a separate chassis. Each of the modules within the RF head and the receiver mainframe will be described in further detail in the following sections.

9.2 RF HEAD

All of the RF circuitry of the WASS receiving system is contained within the RF head. The incoming signals from the antennas are down-converted in the RF head and amplified to a sufficiently high level to be transmitted through coaxial cables to the receiver mainframe. The local oscillator and calibration reference oscillator signals are developed within the RF head and routed directly to the point of application, thus minimizing the losses at the relatively high frequencies and the instabilities which result from transmitting the relatively short wave length of the received frequency through long transmission lines.

Figure 9-1 is a block diagram of the WASS RF head. The received signals at 1090 MHz from the antennas are applied to the inputs of the mixer preamplifiers through directional couplers. These directional couplers are used to apply a reference signal at 1090 MHz to the input of the receiving system in order to monitor system drifts. The reference signal is generated in a stable oscillator, the output of which is split into equal amplitude and phase signals and applied through equal length transmission lines to the coupled port of the directional coupler in each channel. The output of the directional coupler is connected directly to the input of the mixer preamplifier.

The mixer preamplifiers consists of five carefully matched identical channels. Suitable multichannel/matched mixer-preamplifier units are available commercially, such as the RHG unit which is presently in use on the experimental WASS system.

The local oscillator signal is generated in a high power local oscillator similar to the calibration reference oscillator. Its output is split into five equal-amplitude and phase components and applied to the local oscillator inputs of the mixer preamplifiers through isolators to provide additional interchannel isolation. Interchannel isolation is essential to high accuracy in the WASS system. The local oscillator is provided with automatic frequency control provision capable of acquiring the ± 3 MHz stability signals from the airborne beacons and tracking them

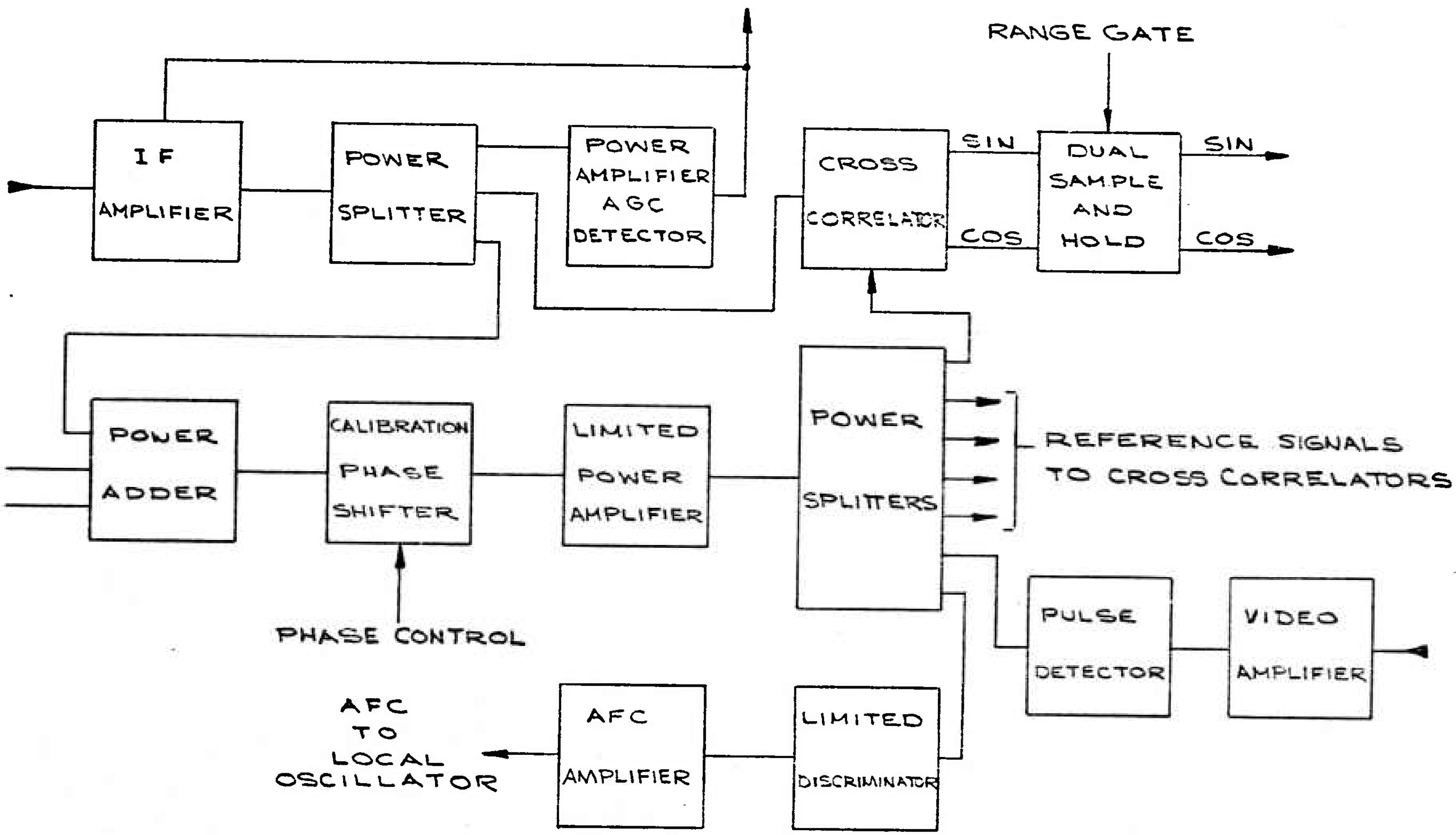

FIGURE 9-2

TYPICAL RECEIVER CHANNEL (1 OF 5) WITH REFERENCE GENERATING CIRCUITRY

within approximately 100 KHz to minimize effects due to frequency offsets in the system.

9.3 RECEIVER MAINFRAME

Figure 9-2 is a block diagram of a typical receiver channel and the associated circuitry for developing the cross correlator injection reference, the automatic frequency control, and the output video pulses. The remaining four receiving channels are identical.

The IF signal from the receiver RF head is applied to the input of the IF amplifier. This IF amplifier accepts the relatively low level signal and amplifies it to a level of aproximately 0 dBm. The phase and amplitude responses of the five amplifier channels are closely matched and the remainder of the circuitry is linear.

The high level output from the IF amplifier is split into three equal amplitude components. One of these outputs is applied to the input of a power amplifier/AGC detector combination which amplifies the signal to a still higher level and linearly detects it in a fast attack, slow decay detector. The outputs of the five AGC detectors are connected in parallel so that the AGC control to the IF amplifier channels is provided by the amplifier having the largest input signal. This eliminates the possibility of distortion due to overdrive.

A second output from the power splitter in the IF amplifier output is applied to the input of the dual cross-correlator which multiplies the IF signal with a reference derived from the combined outputs of three of the receiver channels and generates DC outputs proportional to the quadrature components of amplitude of the signal at that antenna. These DC signals are applied to the inputs of a dual sample-and-hold module which is controlled by the range gate. The sample-and-hold modules sample the heights of the pulses coming from the cross correlator and convert them into a slowly varying DC signal form suitable for analog-to-digital conversion and application to the computer for processing.

A third output from each of the power splitters of the three receiver channels sampling the outputs of the 17, 22, and 24.5 foot height antennas is applied to one of the inputs of the power adder. The line lengths of the coaxial cables connecting these inputs are adjusted properly to steer the resultant array beam to an elevation of approximately 3.5 degrees. This has been determined by computation to provide the optimum array pattern for use in generating the coherent detector reference. Figure 9-3 is the

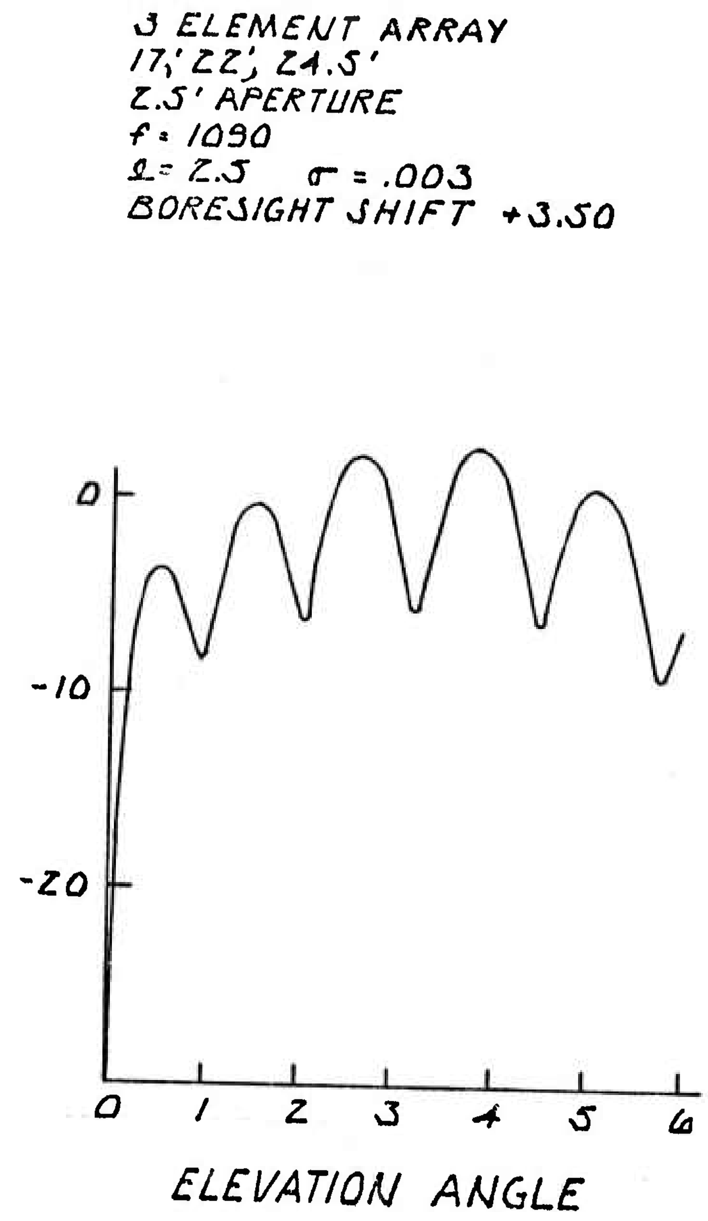

FIGURE 9-3 COMBINED ARRAY PATTERN OF THREE ANTENNA ELEMENTS 17, 22 & 24.5 FT ABOVE GROUND & PHASE SHIFTED TO POINT UP 3.5° IN ELEVATION.

resultant array pattern showing that the input level into the reference channel varies less than 12 dB between 0.15 degrees and 6 degrees elevation angle. Figure 9-4 is a similar antenna pattern for a single antenna above a ground plane, such as was used in previous WASS implementations. It is obvious from looking at this second pattern that areas occur where insufficient signal is available for adequate cross correlation. This effect could be eliminated by switching between antennas, but the resultant circuitry would be more complicated and the overall performance would undoubtedly be poorer because of the more complicated circuitry and the requirements for making a level decision. The peaks of the single antenna signal are also approximately 6 dB lower than that of the combined.

The reference signal from the three channels is applied to a calibration phase shifter. This calibration phase shifter provides a capability for rotating the outputs of the cross-correlators through a full 360 degrees. This makes possible the measurement and elimination, if desired, of the effects of zero drift, unequal sine and cosine channel gain and quadrature error in the cross-correlators.

The output of the calibration phase shifter is applied to the input of the limiter/power amplifier. The limiter/power amplifier is capable of taking the output of the phase shifter, which varies over several dB in amplitude, and supplying a constant output of sufficient amplitude for division into equal amplitude signals for application to the cross-correlator inputs and for application to the limiter-discriminator and pulse detectors. For proper operation the limiter should be capable of handling input level variations of at least 30 dB with no more than 5 degrees phase shift variation over the dynamic range. Such units are readily available commercially.

One of the outputs of the reference channel is applied to the input of a limiter-discriminator. This limiter-discriminator need have a relatively limited dynamic range since its input signal is already limited. The output of the discriminator is amplified in the AFC amplifier circuitry and provided to the local oscillator automatic frequency control input. It is essential that the limiter-discriminator function well on pulse type signals and that it be extremely sensitive to frequency variations in the region immediately around the center of the intermediate frequency amplifier band.

Still another output from the reference channel is applied to the input of a pulse detector. This pulse detector responds to the envelope of the reference channel pulse signal and provides an output which is amplified in a video amplifier and made

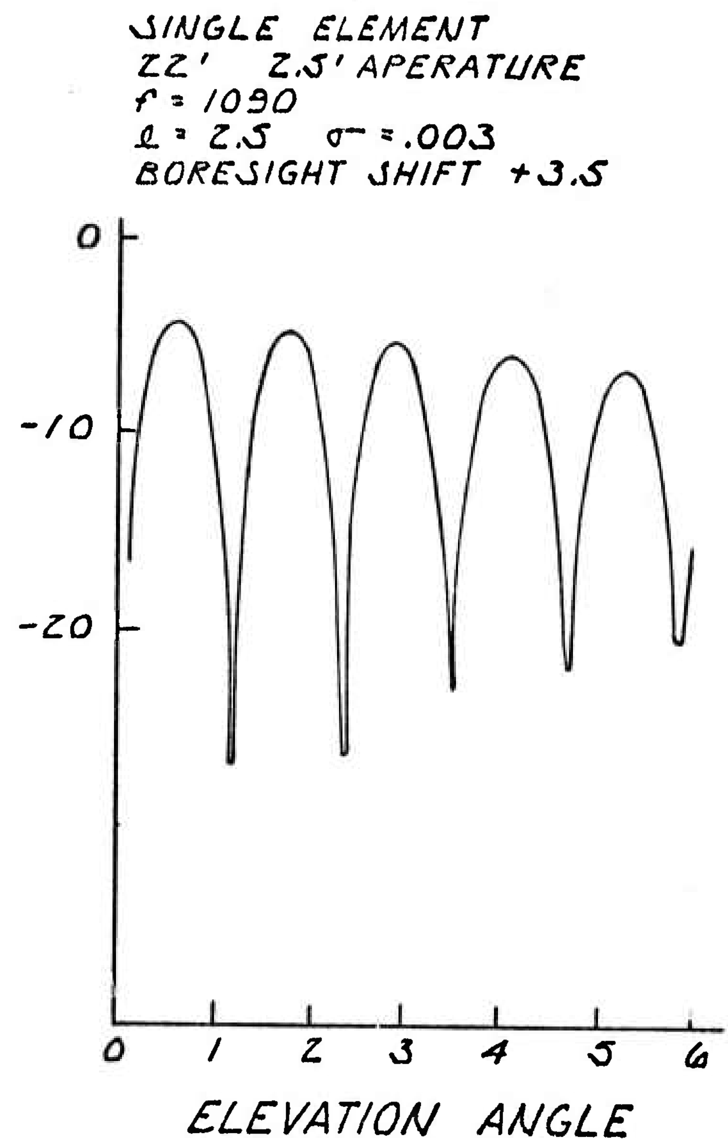

FIGURE 9-4 RESPONSE OF A SINGLE ANTENNA ELEMENT 22 FT ABOVE GROUND.

available for display. This allows comparison of the detected pulse with the range gate pulse. It is also possible, if desired, to generate a control pulse from the detected pulse for an alternate means of control of the sample-and-hold circuits.

9.4 AUTOMATIC CALIBRATION

Automatic calibration is accomplished by use of the calibration reference oscillator and a reference beacon located near the runway at a considerable distance from the WASS array. The computer controls these two sources to exercise the WASS system. The calibration reference oscillator would normally be operated during times when there is no activity in the vicinity, although it could be programmed to operate in an interleaved mode.

A pulse modulator in the calibration reference oscillator output would generate an RF pulse at 1090 MHz for application to the receiver inputs. A range gate input to the sample-and-holds in the receiver outputs would be operated at a time equal to the propagation delay of the receiving system plus a fraction of the pulse width later in order to acquire the amplitude and phase of the reference input signal. Simultaneously, the programmable attenuator in the reference oscillator output would be operated by the computer to vary the input signal level over the range of normal operation. The resultant receiver output would be compared with the outputs obtained during the previous calibration and if sufficiently different would be stored for subsequent use in error correction.

The remote beacon transmitter would be interrogated in a fashion similar to that of the onboard beacon transmitter and the resultant WASS outputs would be compared with the known correct values for the location of the fixed beacon. These outputs would be used for real time correction of the position data resulting from antenna wind sway and for differential heating effects on the tower position. These data outputs would also be valuable in assessing the system performance in order to determine the need for manual calibration and/or maintenance. The remote beacon source would be located at a height above the ground which provides optimum phasing between the two received signal components for best angle resolution. Two or three separate heights would be required to properly test all antennas for system performance.

9.5 MANUAL CALIBRATION CHECKS AND ADJUSTMENTS

Manual calibration would be accomplished at times when the system is not in use, such as in the early morning hours. Manual calibration would also utilize a remote beacon transmitter inter-

rogated in a fashion similar to that of an airborne transmitter. In contrast to the beacon transmitter used for automatic calibration, the manual calibration transmitter would be located at a height where the maximum of the received field is located precisely on the center antenna of the three antenna combination being calibrated. No WASS solution is possible under these conditions but the system calibration is least sensitive to the value of the reflection coefficient of the intervening surface which is the least known parameter. With this condition imposed, the relative amplitudes and phases of the three channels being calibrated would be adjusted to precisely match the computed voltages for that geometry. A different reference beacon height would be required for each of the three combinations of horns. However, since some of the channels are common to the different triplets only the new channels would be adjusted in each succeeding case, noting the variation in the common channels.

Prior to adjustment of the amplitudes and phases, the cross correlators would be adjusted to provide a perfectly centered circle when the calibration phase shifter is rotated through its 360 degree range. It is not anticipated that this adjustment would be required except for initial calibration.

This manual calibration is for the purpose of electrically aligning the equipment accurately. This should be done periodically so that the equipment errors will always be sufficiently small that the automatic calibrations can be performed. The automatic calibrations enable the computer to correct for reasonable system errors but cannot be expected to accommodate gross errors.

9.6 SYSTEM MAINTENANCE CONSIDERATIONS

Because of the completely solid state design of the WASS receiving system, no routine maintenance of the system is required. The automatic calibration features of the system provide a routine means of monitoring the system performance using the system computer. If one of the system channels should degrade to the point where it is no longer useful or fail completely, the computer would recognize this condition immediately.

The WASS receiving system is completely modular in design with the modules being broken down approximately the same as the blocks in the system diagram. Module interconnections are by means of coaxial cable for signal connections and by means of multiconductor cables for power and control functions. In case of a failure in the system a scan of the module test points by the computer would quickly isolate the defective module and it could

be removed from the system and replaced by an operating module or repaired on the spot.

All of the modules used in the system would be field repairable by replacement of individual failed components, with the exception of some submodules such as sample-and-hold circuits which are hybrid units and are normally molded in plastic or hermetically sealed by the manufacturer. These submodules would have to be returned to the manufacturer for repair.

Because of the multichannel design of the equipment, with the exception of the reference generating circuitry, failure of a module would result in system degradation rather than in complete loss of function. The ability to rapidly isolate a failed module would minimize the down time even in the event of a complete system failure.

SECTION X
DATA PROCESSING

10.1 GENERAL CONSIDERATIONS

Figure 10-1 is an overall block diagram of the WASS landing system. The computer inputs antenna voltages from the WASS channels, and from the azimuth measuring receiver channels, all voltages being converted to digital form by the A/D converter. Range measurements are made directly in digital form by the range measuring circuit in the Interrogation and Ranging (IR) unit, and are inputted directly to the computer. Computer output data consists of target aircraft position coordinates, together with such other discrete display information (such as self-test status, quality measures, and ID codes) as may be desired. Outputs are stored in digital registers or analog sample-and-hold circuits, which hold the desired quantities for the display devices to be employed: cathode ray tube for position information, lamps, meters, aural indicators for the rest.

Two phases of system development are recognized: the early phases during which system parameters and hardware are being changed in arriving at a "final" design, and the later phases during which a production system will be designed and manufactured. For the developmental phases, a general purpose minicomputer will be required. For the production system, when the programming, etc., may be sufficiently finalized for operational needs, a less costly microprocessor is envisioned. By the term microprocessor we here mean a smaller dedicated computer, in which program steps are stored in a Read-Only Memory (ROM), and the input/output devices available to the human operators may consist of thumbwheel and other switches and the normal display devices. During the developmental phases, the minicomputer will be supplemented with an input/output terminal to permit insertion of program and data, to facilitate programming changes and to effect system debugging. This terminal may consist of a teletype unit (including tape punch and reader), as indicated in the block diagram, or it may consist of some other terminal device. Additionally, a digital tape unit is deemed advisable to record real time data during flight evaluations so that flights may be "played back" in order to observe system operation at the leisure of the development engineers.

The computer will perform the following functions; each of which is envisioned as the software equivalent of a subroutine.

(1) <u>WASS Computations</u>

From the antenna voltages (two voltages per channel to rep-

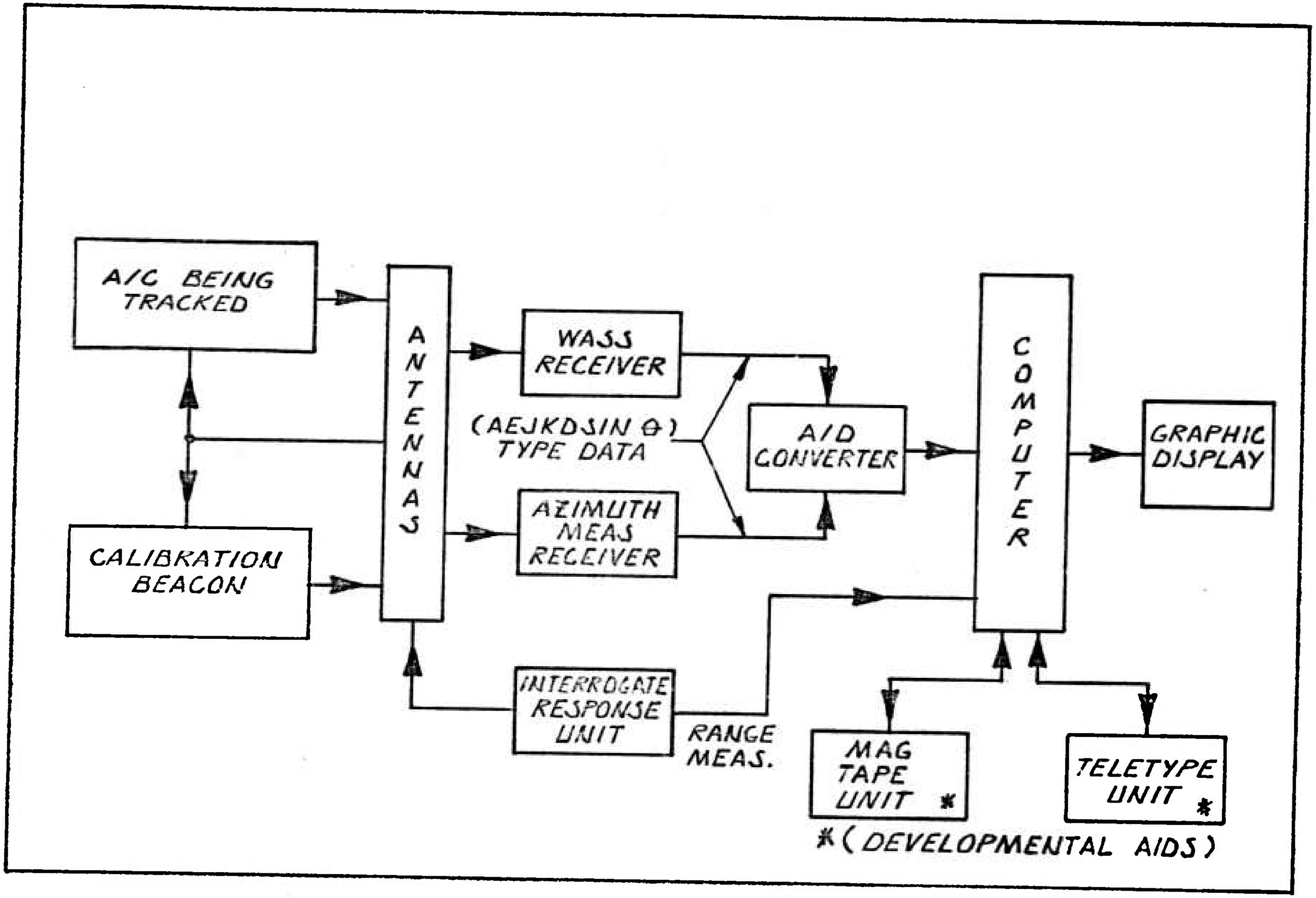

FIGURE 10-1 SYSTEM BLOCK DIAGRAM

resent in-phase and quadrature components of the received signal) a two-or-one component solution is accomplished by the WASS subroutine. This includes selection of suitable antenna combinations for the best data reduction accuracy, reversion to a one-component solution when the ground reflected component is absent, and the activation of flag bits whenever a solution is not possible. Output to main routine consists of the geometric vertical angles of ar ival of the two components, the ratio of their amplitudes, and relative phase between them.

(2) Azimuth Computations

A simpler subroutine will input data from the azimuth measuring receiver and output azimuth angle of the aircraft. This will be based on a comp ter equivalent of monopulse operation.

(3) Calibration

Data from the calibration beacon is obtained from the receiver outputs, in response to an interrogation code that does not trigger the airborne units. Since the position of the calibration beacon is known (to the computer), the relative phase and amplitude response of each channel (including the azimuth monopulse channels) can be reduced to a common basis, despite variations in phase and amplitude response among the various receiver elements. Thus, the calibration procedure consists, in effect, of comparing each channel complex output with what it should be and, by taking a complex ratio, determining a correction factor to be applied to all subsequent data. The "should be" values for comparison may be inserted as constants, or, alternatively, the geometry of the beacon to antenna installation may be inserted into the computer, with an initialization subroutine used for computation of the values, which are placed in the permanent store in the computer.

(4) Geometric Calculations

Based upon the positioning of the antennas relative to the origin of the coordinate system, the conversion to position coordinates of the two arrival angles, and range information from the IR unit, is accomplished from simple geometric considerations. The final output consists of the values of X, Y, and Z of the target, referred to the origin, which is most conveniently chosen as the intersection of the glide slope paths with the centerline of the runway, i.e., the glide path intercept point (GPI).

(5) Data Smoothing

A WASS and azimuth computation may be made for each response

pulse (or group of pulses) received from the airborne transponder. Thus, hundreds of geometric determinations of aircraft position can be made per second, though the number required may be much less. By making an optimized estimate of aircraft position and velocity (each having three Cartesian components) based upon many past measurements, a computation of best estimated present position may be made. The set of six numbers (X, Y, Z, $\dot{X}$, $\dot{Y}$, $\dot{Z}$) is referred to as the "state vector" of the aircraft. The state vector estimate will be accomplished by the data smoothing routine, which improves the accuracy of the data displayed for the operator. A Kallman type filter may be implemented for this purpose. As a byproduct, the error matrix associated with this type of filtering could be utilized to control the interrogation rate, i.e., when the data indicates high "noise" levels (such as may be occasioned by actual noisy conditions, missing responses, or aircraft buffeting) the interrogation rate could be increased above its normal value. This would minimize interference to other users of ATCRBS, yet assure sufficient interrogations for the short periods when higher interrogations rates were needed.

(6) Self Test Routine

The calibration beacon for the system roughly corresponds to the corner reflectors of a conventional PAR (Precision Approach Radar). When the corner reflectors are visible on the radar display in their usual positions, the radar is judged sound. In a like manner, for the system under discussion, when all of the receiver voltages (for the calibration beacon signal) are within a tolerance limit of those pre-calculated for the known geometry of the beacon position, and the range measurement is within tolerance of its known value, the overall system is judged sound. This task will be accomplished by the computer as a cyclical occurrence during normal system operation.

(7) Search/Track

Each response must be regarded as a potential "track". When multiple responses from the same region in space are obtained, the computer will establish a "track" and output coordinates to the display. In conjunction with the data smoothing, the computer must maintain an acceptance "window" within which data is identified as belonging to a single target. This involves using the present best range estimate, and a tolerance zone about it. When a track is established, a precision timing circuit based on best range estimate will permit windowing receiver output so that receiver channel outputs may be gated appropriately. It is this feature of the design which will allow tracking of multiple targets. Each target is tracked in the computer, and appropriate

range gates are generated so that separation of target information is achieved. Separate tracks can be maintained as long as responses from separate aircraft do not overlap. If the duration of the transponders' transmissions are 21 microseconds, for example, the minimum spacing of the aircraft is approximately 4 miles.

(8) Display Generation

The computer may be called upon to generate the display, wherein it is feasible to consider the generation of special symbols, alphanumerics, etc. However, as mentioned under the description of the display elsewhere in this document, we envision that an adequate display will consist merely of two spots on a cathode ray tube, showing the position of the aircraft referenced to fixed graticule lines on the face of the display. Thus, the coordinates computed by the computer in digital form, need merely be converted to analog voltages for oscilloscope beam deflection, and the two spots written in sequence at a rate producing satisfactory flicker characteristics. This may be done with simple display electronics. Scale changes may be made through the computer.

(9) Initialization

A separate subroutine will be invoked when the equipment is initially set in operation. This enables operator insertion of the geometric factors to be made: antenna positions relative to glide slope intercept point, calibration beacon position, antenna foreground slope (if necessary), and other constants pursuant to system operation.

10.2 COMPUTER REQUIREMENTS

To accomplish the above tasks, a minicomputer in the class of the Data General "Eclipse", or the Hewlett Packard 21MX series, is envisioned during development phases. For the ultimate operational design, a specially designed microprocessor is appropriate. Listed below are the salient features required:

(1) Word Length

The computer should employ a word length of at least 16 bits, which is obtainable in readily available minicomputers. This enables a single word to represent most of (perhaps all) of the variables in the computations on a "single precision" basis with sufficient accuracy for system needs, i.e., one part in 2^{16}, or 65,536. Where more precision is required (as could be possible for internal or intermediate variables) two or more computer words

("double precision") per entity can be employed.

(2) Memory Size

The computer memory (or store) should have sufficient capacity to store the necessary programs, to store input constants and intermediate data pursuant to computations, and to store commonly used subroutines. A large segment of memory space will be needed to store a high level language compiler (such as Fortran), enabling rapid programming changes to be effected during development. At least part of the store should employ semiconductor devices (as opposed to magnetic cores) in order to obtain high speed operation. Memory size is currently estimated at 16K.

(3) Hardware Computation Features

There are several computation features which are best resident in the "hardware" or "firmware" of the computer, rather than as subroutines in the main memory, because the speed of their accomplishment is much increased thereby. For example, the processes of multiplication, division, and floating point arithmetic would normally be achieved this way. Certain other, normally time consuming computations, such as trigonometric functions (used frequently in the WASS routine), may also be "wired in" through the utilization of table look-up routines involving a semiconductor ROM (Read-Only Memory), thereby greatly increasing the speed.

(4) Microprogramming

Microprogramming allows program structured commands to be coded into a more concise language than is possible using conventional machine language. In effect, the Control function for the Central Processor function within the computer, functions in a manner that can be altered by the programmer, rather than upon a fixed-wired, or Read-Only Memory basis. To achieve microprogramming, the computer is equipped with a Control Store; for the purpose at hand, a Writable Control Store enables the microprogram to be changed, if necessary, as the development of the system proceeds. Here are the desirable features that obtain from microprogramming:

a. System Speed

Microprogramming can increase the system speed, because microinstructions are executed from 5 to 10 times faster than machine language instructions. Thus, a frequently used software subroutine will execute much faster when in the form of a microprogram. With additional registers available to a microprogram, the number of main memory accesses can be greatly reduced. This

is particularly significant for the WASS real-time system, which is compute-bound, i.e., the I/O is performed faster than the computation.

b. Memory Space

By converting software routines into microprograms, main memory space is freed for other purposes. The routines remain instantly callable, as opposed to routines which are relegated to disc or drum storage, which require additional time delays in accessing.

c. Special Functions

The computer instruction set can be expanded to perform functions that are oriented to specific applications. Thus, the general-purpose computer can become a special-purpose machine uniquely adapted to a particular environment. In the WASS computations, there are a considerable number of square root and trigonometric functions, which account for a large part of the compute time. Rendering these to microprograms could make faster compute times possible.

d. Growth Toward Microprocessor System

The ultimate system would not need the flexibility required in development; rather, it would be designed for minimum cost and a minimum of operator controls. Thus, the ultimate system may employ a microprocessor. If the specific microprocessor can be identified at the beginning of the software development phase, then microprogramming of the minicomputer used during development may be done in a way which closely simulates the specific microprocessor to be utilized later. In this manner, the software developed during the design phase will be more directly applicable to the "ultimate" system, and software costs are greatly reduced.

(5) Direct Memory Access

Under normal computer operation, input channels are scanned successively and purged of new data, or they may operate through the computer interrupt function whenever they produce new data for computation. In either event, the central processing function in the computer is temporarily halted, the data passes through the central processing unit on its way to the computer store, and time is lost. With direct memory access, a direct flow path between input devices and computer store is established in such a way that a minimal effect is produced upon the computation task. Thus, where a large amount of data must be inputted, this feature can

have a very beneficient effect upon computation time, and should be included during the development phases.

(6) Power Monitor/Automatic Restart

Without special provisions, power interruptions or transients can play havoc with a computer. For example, with core memory, suppose an instruction word is being fetched, and the power is interrupted during the re-write cycle. The instruction could be lost, necessitating re-loading the program to start the computer again, a disastrous situation for the landing system application. With automatic restart, a temporary power storage device is used to run the computer, which, sensing a power interruption, switches the operation to an automatic restart sequence. This is a short program which may be prepared by the user to cause the computer to shut down "gracefully". Data in registers may be stored, the program sequence counter reset to the beginning of the program, and stored constants and program steps conserved. This feature is a must for the developmental and "final" versions of the system.

(7) Other Features

Other desirable features for the developmental computer include automatic program load (permitting program manipulations and insertions without a lot of operator trouble), real time clock (for sequencing events outside the computer with computer operations), and parity error detection output (a sort of self test for the computer memory devices).

10.3 MICROPROCESSOR UTILIZATION

With the flexibility and power of the general purpose computer discussed above, the WASS system may be developed and subjected to considerable change during the first phases of the system development. When the software and computer operation is firmed up, a special purpose computer may then be designed around currently available microprocessors. Consideration of the design for such a computer, as they relate to the WASS equations (the most difficult of the computational tasks necessary in the system) has been made by Data/Ware Development Inc. of San Diego. The results of that consideration are contained in Data/Ware Report T-94-577, entitled "WASS Digital Controller", an edited excerpt from which follows:

"1. Introduction

The Teledyne Micronetics Wavefront Analysis and Spatial Sam-

pling (WASS) system equations are summarized in a memorandum, Basic WASS Equations, by Dr. Steven Weisbrod.(1) The desired digital iteration rate for the solution of these equations is 1,000/sec.(2) From the computational point of view the most difficult requirement relates to the number of multiplications and divides that are required plus special functions such as square root and arc tan.

Two approaches to the computational problem are apparent. One would be to use an existing minicomputer/midicomputer, in which case the speed of solution would be marginal. The other is to assemble a general purpose digital controller using one of the new microcomputer chip sets. In particular, the second approach would be based on extremely fast bipolar chips just introduced by Monolithic Memories and by Intel. These chips are bit slices, i.e., the Monolithic Memories 6701 is a 4-bit slice. Hence it is possible to place four of them in parallel and to obtain a 16-bit computer. The Intel 3002 is a 2-bit slice.

The advantage of the microcomputer approach lies both in the speed at which microinstructions can be executed (300 nanoseconds or less) and the fact that one can create his own instruction set. The latter is accomplished by defining a sequence of microinstructions, called a macroinstruction, which could for example perform a complex multiply or divides. Using the 6701 microcomputer chips, it would be possible to assemble the central processor with 25 to 30 IC's. Memory would take perhaps another 16. I/O might add another 15 or so. Thus the entire processor consists of perhaps 60 to 75 TTL chips".

"2. <u>Problem Analysis</u>

Going through the 18 WASS Equations and the 7 Tests shows that there are 106 multiply/divides and 64 adds/subtracts to be performed. However, this information is not sufficient to estimate solution times. The general problem is that there are many short instructions required before it is possible to execute the major operations of multiply/divide and add/subtract. These are the "red tape" or data manipulations to fetch data from core memory or Random Access Memory (RAM) and to store back intermediate results. Thus while it is possible to say that dividing one complex number by another takes 8 M/D (Multiply/Divides), and 4 A/S (Add/Substracts), when it is actually coded up for a typical computer, it is apt to take 34 to 40 instructions. This in turn does

(1) See Section 3 of this document.
(2) This is an upper bound. In practice, interrogation rates less than this may prove entirely adequate, and will produce less "fruit" interference for other users of the ATCRBS beacons.

does not take into account calling the subroutine, returning to the original program, and any scaling required.

Looking then just at the present WASS equations and neglecting scaling, input/output, and any smoothing of the final data in a digital filter, or special operator inputs, the number of instructions might be estimated at 120 "long" instructions (multiply and divide) and 424 "short" instructions. If one takes for execution times typical figures of 6 microseconds for long instructions and 2 microseconds for short, one obtains 1,568 microseconds. Applying a 50% safety factor (always a good idea during problem definition stage), this comes to 2,352 microseconds or an iterative solution rate of 425/second.

One then concludes that an appropriate minicomputer, or perhaps a larger, more powerful midicomputer, could be employed to solve the WASS equations. Even a powerful minicomputer would appear to be marginal in performance.(1) However, there are midicomputers such as the Varian 73 which are powerful and seemingly could meet the requirements or come close.

The suitability of a commercial mini/midicomputer for field installation in the ultimate WASS system would then have to be assessed relative to cost, reliability, and operating procedures".

"3. Digital Controller Based on Microcomputer Chips

The recent introduction of bipolar (Schottky TTL) microcomputers by Monolithic Memories and Intel (Texas Instruments is about to announce theirs) has made it possible to design ultra-fast and very small parts count digital controllers. These devices can emulate existing minicomputers because the user creates his own instructions through sequences of microinstructions. These "computer slices" are the next step beyond the popular 74181 Arithmetic Logic Unit, a TTL device which has been to date the basis for many TTL minicomputers. The 6701 and the 3002, however, each replace 25 ordinary TTL IC's. Hence 4 6701's (enough for a 16-bit computer) replace 100 IC's. It is expected that such chips will obsolete all existing minicomputers. The era of, Design your own Computer, has arrived.

The 6701 4-bit microcomputer slice contains the ALU (Arithmetic & Logic Unit), 16 general registers in a RAM, shift matrices, Q register to facilitate multiplication and division, a control ROM for input microinstruction control, and provision for data in and data out. These chips are designed so that they can be directly attached, one to the other, to create longer word lengths in 4-

(1) But only at the assumed rate of 1,000/sec.

bit increments.

The user can readily create a basic computer instruction set through defining his instruction set by microprogramming such as the following:

BASIC COMPUTER INSTRUCTIONS

1. LOAD REGISTER
   a. From address specified by instruction
   b. From calculated address specified by register

2. STORE REGISTER
   a. To specified address
   b. To calculated address

3. COMBINE REGISTERS
   a. COPY: $A \rightarrow B$
   b. ADD: $B+A \rightarrow B$
   c. SUBTRACT: $B-A \rightarrow B$
   d. AND: $B \wedge A \rightarrow B$
   e. OR: $B \vee A \rightarrow B$

4. MODIFY REGISTER: SHIFT
   a. Shift Left : $BX2 \quad B$
   b. Shift Right: $B \div 2 \quad B$

5. LOAD PROGRAM COUNTER(JUMP)
   a. With address specified by instruction
   b. With calculated address specified by register

6. LOAD PROGRAM COUNTER AND SAVE OLD VALUE(JUMP TO SUBROUTINE)
   a. With address specified by instruction
   b. With calculated address specified by register

7. TEST(RESULT OF PREVIOUS COMBINE OPERATION)AND LOAD P.C. IF:
   a. Result was zero
   b. Result was negative
   c. A carry was generated

8. INTERRUPT: Store old PC and load mixed value

This set of instructions would be augmented for a particular application, such as the one being studied. In particular, multiply and divide would be microprogrammed as well as operations on complex numbers. A macroinstuction runs much faster than a series of normal instructions in a minicomputer because one does not have

to wait for a complete cycle of core memory for each instruction fetch. The microinstructions can be obtained in a minimal time (50 nanoseconds or so) rather than in a microsecond.

A computer with an instruction set similar to that above would have a total chip count of 24 IC's plus memory. For this Data/Ware would propose the use of the Fairchild 93415 1024-bit RAM (bipolar) as the element of the RAM Memory. 16 such RAM's would yield a 1024x16 word memory which can be accessed in 100 nanoseconds or so.

Note that the entire design is bipolar TTL and would run off a single 5V power supply. Because of the small parts count, fabricating the system would be simple. The principal items of cost are the four 6701 chips, which are expected to sell for around $50 each next year and the sixteen 93415 RAM's, which would sell for $22 each. The other TTL parts would be relatively inexpensive. This system is extremely attractive from every view point -- reliability, cost, performance, troubleshooting, etc.

After the program is debugged, demonstrated, and finalized, it would be possible to replace the RAM with Read-Only Memory (ROM) so that there would be no problem of destroying the stored program in the field. For initial operation it is suggested that the RAM memory would be more convenient".

"4. Summary

Early in 1974 Data/Ware placed in operation its powerful microprogrammed Signal Processor using 400 TTL IC's. This design and the present generation of minicomputers are now made obsolete by the new bipolar microcomputers. Systems such as WASS are readily implemented by the bipolar microcomputer chips, such as those from Monolithic Memories and Intel. Core Memories similarly are obsoleted by RAM's and ROM's".

SECTION XI
DATA DISPLAY

11.1 GENERAL DESCRIPTION

Figure 11-1 shows a possible display subsystem which operates on computer outputs to display aircraft position on a cathode ray tube. The display technique illustrated is easily implemented with a minimum of circuit development work and, thus, is recommended for use in the development phase of the project. It can be used as a basis for more refined human engineering as experience with the system is gained.

The display philosophy is based on implementation of a radar-type display nearly identical to that which is currently used in Precision Approach Radar systems. In the PAR systems, two displays are produced. One is a range versus vertical angle display, the other a range versus horizontal (lateral) displacement.

In the system under consideration the computer determines aircraft present position in three Cartesian coordinates. Thus, the distortions which are produced by antenna site offset from runway center line need not distort the geometry of the display, which can operate directly in the Cartesian coordinate measurement system. The two display points on the oscilloscope depicting the glide path intercept point on the ground appear at the intersection of rectangular coordinate grid lines marked on the cathode ray tube viewing screen. At the top of the screen represents the aircraft position in coordinates of vertical height (Z) versus horizontal range (X) with calibrations provided in feet for the vertical scale and in miles for the horizontal scales. The display at the bottom of the cathode ray tube shares the same scaling for the X coordinate reproduced along a second grid line marked X2 in the illustration. Here the vertical dimensions of the cathode ray tube correspond to lateral deviations of the aircraft from the prescribed glide path. The fixed reticles on the surface of the display area include not only the coordinate lines for the axes but they also include various glide path angles which in this instance appear as straight lines on the upper display area. Thus, the operator views an elevation view and a plan view of the aircraft as it moves toward the ground path intercept point. The aircraft itself appears as an intensified spot on the surface of the cathode ray tube in the two positions which define the aircraft position in space.

Operation of the display device is simple and straightforward. The X, Y, Z coordinates of the aircraft as computed by the tracking algorithms within the computer are converted to analog

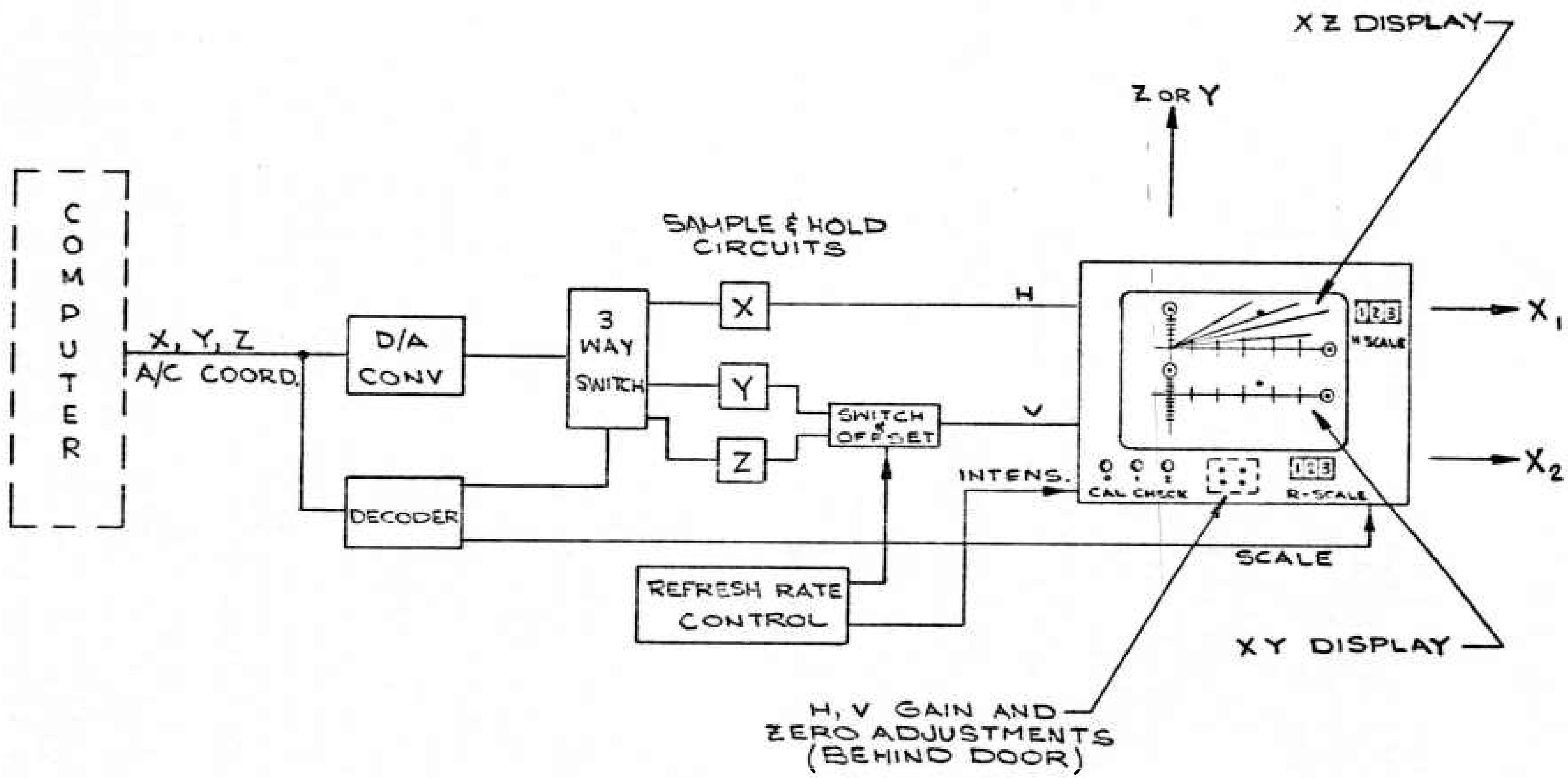

FIGURE 11-1
DISPLAY SUBSYSTEM

voltages by means of a digital-to-analog converter. Some of the bits in the messages from the computer may be used to designate which coordinate is being received by the D to A converter, which then allows a three way switch to operate to connect the analog output voltages to the three sample-and-hold circuits shown. Thus, analog voltage representations are continuously available for the X, Y, Z coordinates of the aircraft. The X coordinate is continuously applied to the horizontal deflection circuits of the oscilloscope display. Y and Z coordinates are switched alternately into the vertical channel of the display so that a time sharing produces the dual display mentioned above. This time sharing operates at a high rate of speed above a visible flicker rate, so that the two spots representing aircraft positions appear simultaneously as far as the viewer is concerned.

Scaling of the display is controlled by the computer, which of course is under manual control of the operator. Thus, part of the digital information from the computer designates which scales are applicable to the horizontal and vertical displays. This digital information is likewise decoded and used to actuate a numeric LED display near the cathode ray tube area so that the appropriate scales of the reticles on the cathode ray tube are designated to the operator.

A calibration check is accessible to the operator and operates as follows. An operator pushes button 0 which causes digital information to be simulated corresponding to X, Y, and Z all set to zero, for which case the two spots should move to the origins of the cathode ray tube axis intersections. When the button marked "one" is pushed, the spots should move to the small engraved circles along the vertical axis of the display corresponding to an X value of 0 with Y and Z set to calibrate values. In a similar manner, pushing button number "two" should cause the spot to move to areas along the X axis. Adjustments accessible for maintenance purposes to assure these calibrations are placed behind the front control panel. A refresh rate circuit is used to operate the switch which switches the Y and Z input information to the vertical channel and also to intensify the cathode ray tube display in order to produce the intense spots representing the aircraft. Controls not shown would include brightness control, and of course all of the other controls associated with operation of the system.

Thus, the display device consists simply of a cathode ray tube with a dual channel vertical input so that two spots may be positioned on the display to represent the three coordinate positions of the aircraft in flight. Deviations of aircraft from appropriate glide path, both in altitude and laterally from the runway center line extension, are easily discernible by the oper-

ator in a manner that closely follows present usage of precision approach radars. The design is simple and straightforward and involves inexpensive components. For initial development the cathode ray tube display itself could be simply a laboratory type low frequency oscilloscope supplemented with the circuits necessary for conversion switching and DC sample-and-hold.

SECTION XII
TEST AND EVALUATION PROCEDURES

12.1 GENERAL DESCRIPTION

It is the main intent of the current effort to demonstrate the capability of the WASS technique and its applicability to provide precise aircraft information in its final approach to the runway. In order to test this system and to provide proper evaluation, it will be necessary to set up the WASS in a real environment involving real runways and real aircraft. For this purpose, it is now planned that an Air Force base in the vicinity of Rome Air Development Center would be utilized. Specifically, what has been planned is that the WASS array would be set up at an appropriate place about 500 feet to one side from the center of the runway. An Air Force aircraft specifically assigned to this job would be independently tracked by radar and/or optical devices to provide accurate information on its position at all times. This aircraft will approach the runway with different glide slopes and tests will be repeated over a period of time to establish effects of different meteorological factors such as rain, snow, fog, etc.

12.2 SPECIAL CONSIDERATIONS

For the purpose of such tests, it will be assumed that range information shall be obtained by calibrating the test aircraft transponder delay. Similarly, no attempt will be made at this time to provide azimuth information. Instead, the effort will be directed primarily to the assessment of the WASS capability to resolve the elevation angle of arrival. Inasmuch as the wavefront analysis capability should be far greater than that which can be obtained through normal techniques it will be necessary to utilize independent optical trackers as mentioned in the previous subsection.

12.3 DATA PROCESSING CONSIDERATIONS

A substantial portion of the overall cost of data processing will be in the computer. The computer, of course, is necessary to provide real time data reduction capability. However, for the purpose of the test several options are open. First, and the most desirable, could utilize a special purpose minicomputer which could be acquired on loan or instrumented purposely for this effort as described in Section 10. An alternate possibility is to use a telephone line to the RADC Computer Center and provide on-line data reduction. Still another consideration would be to record the information on tape and perform the analysis afterward.

The third alternative has a serious disadvantage in that after-the-fact analysis is always less convincing than a real time display. No attempt will be made at this time to interface with any other GCA activity. The display for the purpose of the demonstration will be a very simple one and it is described in Section 11.

SECTION XIII
BUDGETARY ESTIMATE FOR THE WASS LANDING MONITOR

The purpose of the following discussion is to provide the Air Force with a budgetary estimate for the development on an operational WASS Landing Monitor. Two estimates are involved; the developmental estimate which will include the necessary testing and documentation to comply with pertinent MIL Specifications and the production estimate for the cost of operational units. The costs are estimated on the basis of 1974 prices and do not include installation costs which will vary from one installation to another, depending on the complexities of bringing power, interfacing with existing GCA capabilities and if necessary improving the antenna foreground through suitable grading of the first several hundred feet in front of the WASS array to insure a well defined specular reflection.

The WASS Landing System can be divided into major subsystems as described in Section 4 and indicated in Figure 4.2. The budgetary estimate of the various are as follows:

SUBSYSTEM	DEVELOPMENT COST	PRODUCTION COST
WASS Antenna Array (Full monopulse capability)	$ 60,000	$ 20,000
WASS Front End	60,000	20,000
WASS Receiver (Six channels for full monopulse capability)	150,000	60,000
Calibration Beacons and Interrogation Transmitter	30,000	5,000
Interrogation and Ranging Unit	40,000	10,000
Data Processor including on-line computer	100,000	30,000
Data Display and Control	40,000	15,000
SYSTEM TOTAL	$ 480,000	$ 160,000

The above figures indicate that after the initial development costs the cost of a fully operational WASS Landing Monitor will be well under $200,000. It is also estimated that the development of a fully operational system could be carried out within two years.

SECTION XIV
CONCLUSIONS AND RECOMMENDATIONS

The WASS Landing Monitor System has been examined in detail. Various tradeoffs were considered and best engineering judgment was used to optimize performance within reasonable costs. The result of the study clearly indicates that an effective and a relatively inexpensive WASS Landing System could be readily developed and implemented. A typical cost of an operational system should be under $200,000. It should be emphasized that no additional equipment will be required aboard Air Force planes tracked by the WASS Landing Monitor.

In order to verify that the potential benefits of the WASS technique which were experimentally demonstrated in previous efforts can be realized in an airport environment it is strongly recommended that the Air Force undertakes a comprehensive evaluation of the WASS Landing Monitor. To achieve this goal in the most economic way it is recommended that an experimental WASS system limited to tracking the vertical angle of arrival be constructed and tested at an Air Force facility using Air Force aircraft. Such test should be conducted over a period of time to assess potential impact of various meteorological factors such as rain, snow, fog, etc.

If such tests prove successful it is further recommended that a prototype of an operational version of the WASS system with a full monopulse capability be developed. Such a system should then be installed in an operational environment and routinely operated by the Air Force personnel over a period of time. Provisions should be made to insure sufficient feedback to incorporate any changes or improvements which may be indicated. After that operational units should be constructed and deployed at Air Force Bases in the United States and abroad to increase the safety of aircraft landings in adverse weather conditions.